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THE MEASUREMENT OF SOIL WATER[1]

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INTRODUCTION

In the field of irrigation agronomy, investigators need to have acceptable information on the status of the available soil water in the root zone. It is important to know such things as (1) the depth of the active root zone of a given crop on a given soil; (2) the water-holding capacity of the successive sections of the root zone of any given soil; and (3) the quantity of available water in each section of the root zone at any given time or, better still, the changes in that quantity from day to day at any given location.

In the course of an investigation extending over the past 4 years, it has been found that such information may be obtained by the use of the tensiometer.[2] This investigation included a long-continued series of observations on several different crops by means of tensiometers placed at successive depths in the soil at several field locations in widely separated localities. It included also the exploration of several different methods that might be used to convert tensiometric data into values of the quantity of available soil water at each of the successive soil depths at which the tensiometers are set.

The results of this investigation are reported herein.

CATEGORIES OF SOIL WATER

In considering the status of the water contained in the soil, it is convenient to recognize at least two main categories: (1) The unavailable water and (2) the available water. The unavailable water includes that portion which is held so firmly by the soil that it is not free to move as liquid water or to be absorbed by plant roots but which may be vaporized. The available water includes that portion of the total soil water which is free to move in response to gravity or capillarity or to be absorbed by plant roots. The distinction between these two categories is important because only the available water can replenish the underground supply and support plants.

The unavailable soil water comprises (1) water that, while not free to move or be absorbed by plants, may be vaporized and pass into the air; (2) water that is not vaporized under the ordinary conditions of atmospheric temperature and humidity but may be vaporized when the air temperature is raised to the boiling point of water; and

[1] Received for publication October 19, 1944.

[2] An instrument devised and developed by L. A. Richards, of the U. S. Regional Salinity Laboratory, Riverside, Calif.

(3) water that is held as a part of the crystal structure of the soil minerals and may be removed only by temperatures ranging above the boiling point of water. To determine the total water content of a sample of soil, the accepted procedure is to heat the sample to 105° C. in an open container and to keep it at that temperature until it ceases to lose weight. This treatment vaporizes all the available water and that portion of unavailable water in subcategories 1 and 2 but does not differentiate the available from the unavailable water.

The available water includes all the water held by the soil between its saturation point and the upper limit of the unavailable water. In current usage, the category of available soil water is subdivided into (1) the portion that moves freely in response to gravity and passes downward through a well-drained soil and (2) the portion that is held by the soil so strongly that it does not move freely in response to gravity but may move by capillarity or may be absorbed by plant roots. The upper limit of subcategory 2 is referred to as field capacity. This is not, however, a precise or even a very useful criterion, because it is influenced by time, temperature, and the conditions of subsoil drainage.

From an agronomic standpoint, it is chiefly the available soil water that merits consideration. The condition of a soil in respect to its unavailable soil water becomes of agronomic interest only when the available water has been used up or dissipated and some of the unavailable water has also been lost by vaporization. At such a time, if the soil water is replenished by rain or irrigation, a portion of the input is inactivated by restoring the deficit in the unavailable supply. The unavailable soil water may be likened to the dead storage in a water reservoir, i. e., the storage below the lowest outlet. If all the available stored water is drawn off and some of that in the dead storage is evaporated, the deficit in the dead storage must be made up from a new input before any of that input becomes available for use.

This necessary allocation of input water to restore any deficit in the unavailable supply becomes of agronomic importance with soils that hold large quantities of unavailable water. After a protracted drought during which much of the unavailable water may have been lost, a corresponding quantity of the input water must go to make up this loss and the available supply is diminished by that much.

METHODS OF MEASURING SOIL WATER

There are currently in general use three methods of measuring soil water: (1) Gravimetric, (2) electrometric, and (3) tensiometric.

GRAVIMETRIC METHOD

The gravimetric method of measuring soil water involves the collection of soil samples representing sections of the root zone. These samples are taken with a soil tube and transferred to a closed container. The container, with its moist soil, is weighed; it is then opened and placed in a drying oven maintained at 105° C. until there is no further loss in weight. The loss in weight, representing the water content, is then reported as a percentage of the weight of the dry soil.

The gravimetric method yields information as to the total water in the soil. It does not show how much of that water is available. This fact impairs the agronomic value of gravimetric findings. It is possible

to remedy this defect to some extent by determining the wilting-point range for the soils of each section of the root zone for any given location. But the gravimetric method requires the collection of many soil samples and is not practicable for observing accurately the day-to-day changes in soil water at the successive horizons of the root zone.

ELECTROMETRIC METHODS

There are several electrometric methods of measuring soil water. Of these, the one currently used involves measuring the resistance between two electrodes placed in the soil, usually embedded in a gypsum block.[3] The resistance between the electrodes varies inversely with the quantity of soil water and also with the soil temperature. The resistance method is useful in measuring soil water in the range of the wilting point. It is less sensitive to differences in the range of field capacity and above.

Other electrometric methods currently under investigation but not in general use involve measuring the thermal or the electrical capacity of the soil, both of which change as the soil water changes.

TENSIOMETRIC METHOD [4]

The tensiometric method of measuring soil water involves the use of a mercury manometer to measure the tension existing between the soil and the soil water. A porous cup is installed in the soil and connected with the manometer through a flexible copper tube of small diameter. The system is then filled with air-free (freshly boiled) water. Connection between the soil water and the water in the instrument is quickly established through the walls of the porous cup, and the tension of equilibrium is indicated by the height of the mercury column in the manometer. The manometer may be equipped with a scale the units of which are equivalent to 1 mm. of mercury or with a scale on which the smallest subdivision is equivalent to the head of 2 cm. of water; 1 mm. on the mercury scale equals 1.35 cm. on the water scale.

The scale is long enough to measure tensions up to 630 mm. of mercury, or 850 cm. of water, or approximately 0.85 atmosphere. When the tension approaches the upper limit of the scale, bubbles of air or of water vapor are likely to appear in the system. When they do, the readings may be invalid and the instrument must be serviced by refilling it with water after the tension in the soil has been reduced by rain or irrigation. The tensiometer gives precise information concerning soil-water conditions within its range, viz, from zero tension, when the soil is saturated, to approximately 0.85 atmosphere of tension, when most of the available water (80 to 90 percent) has been dissipated.

The tensiometric method appears to be by far the most accurate and the most sensitive one now in general use for measuring the available soil water within the optimum range for plants. This method as it has been used in field investigations, chiefly in irrigated areas, is the subject of the present paper.

[3] BOUYOUCOS, G. J., and MICK, A. H. AN ELECTRICAL RESISTANCE METHOD FOR THE CONTINUOUS MEASUREMENT OF SOIL MOISTURE UNDER FIELD CONDITIONS. Mich. Agr. Expt. Sta. Tech. Bul. 172, 38 pp., illus. 1940.

[4] RICHARDS, L. A. SOIL MOISTURE TENSIOMETER MATERIALS AND CONSTRUCTION. Soil Sci. 53: 241–248, illus. 1942.

FIELD OBSERVATIONS WITH TENSIOMETERS

The investigations here reported were begun in February 1940 with the installation of four tensiometers at successive depths in the soil at the United States Rubidoux Laboratory, Riverside, Calif. The location was in a plot (plot U) allocated to citrus trees. The porous cups were placed at 6, 12, 18, and 24 inches below the ground surface, midway between two 30-year-old Valencia orange trees set 20 feet apart. Subsequently, additional instruments were installed at 36, 48, and 72 inches below the ground surface. After a time, a similar installation was made at another location in the plot so that the records from the two locations could be compared. There was good agreement between the two sets of instruments at the two locations. The observations in plot U at the Rubidoux Laboratory have been continued since 1940.

In 1941 a few tensiometers were installed at the United States Huntley Field Station, Huntley, Mont., and at the United States Yuma Field Station, Bard, Calif. Observations have been continued at these stations. In 1942 several sets of instruments were installed at the United States Scotts Bluff Field Station, Mitchell, Nebr., and observations have been continued at that station. In 1944, 2 sets of instruments with 3 or more tensiometers in each set were installed at (1) the United States Umatilla Field Station, Hermiston, Oreg.; (2) the Irrigation Branch Experiment Station, Prosser, Wash.; and (3) the United States Newlands Field Station, Fallon, Nev. Currently, tensiometric observations are reported regularly from 7 stations, with 57 instruments at 14 locations. These instruments are observed at least once a day, usually early in the morning. The tension values recorded from these observations show the day-to-day changes that occur at each of the successive horizons of the root zone.

An example of the tensiometric data obtained from an installation of seven instruments in a plot occupied by large Valencia orange trees is shown in table 1. The plot was irrigated by sprinklers during the night of May 30–31 and again during that of June 28–29. The depth of input for the tensiometer location was measured by means of eight small rain gages set close to that location.

Table 1 shows that, at the 6-inch depth, the tension rose from 245 mm. on June 18 to 568 mm. on June 28. The morning after irrigation, it stood at 3 mm. or close to saturation. From then to July 15, it rose continuously to 237 mm. A similar sequence of tension values was shown at the 12-inch depth. At the 18-inch depth, the low point of tension was not reached on the morning after irrigation. It was probably reached later that day, and the tension had started up again on the morning of June 30. At the 24-inch depth, the lowest tension probably occurred on July 1. The record of the instrument at the 36-inch depth shows that an irrigation of 0.3 foot did not contribute much water to that horizon. There was some loss of tension after July 2, but the loss was gradual and continuous until July 14. The instruments at 48 inches and at 72 inches showed that there was very little change in the soil water at those horizons during the 4 weeks of the record. It seems evident that at this location the orange trees did not draw much water from below the 36-inch horizon.

TABLE 1.—*Observed tensions at successive horizons of the soil allocated to Valencia orange trees, plot U, United States Rubidoux Laboratory, Riverside, Calif., in 1944*

Date	Tension at indicated depth (inches)						
	6	12	18	24	36	48	72
	Mm. Hg	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*
June 18	245	218	252	482	312	205	168
June 19	272	237	271	510	320	207	170
June 20	306	257	293	528	327	208	170
June 21	352	285	316	542	330	211	172
June 22	397	313	341	553	332	211	171
June 23	454	363	375	566	339	213	174
June 24	479	398	409	571	342	213	174
June 25	511	457	451	----------	345	213	174
June 26	532	522	497	----------	350	215	175
June 27	550	578	510	515	357	217	167
June 28	568	618	514	450	367	218	170
June 29 [1]	3	9	432	538	375	221	173
June 30	50	55	84	270	372	222	172
July 1	67	73	96	106	375	223	174
July 2	78	85	107	109	381	226	175
July 3	88	95	115	114	379	227	175
July 4	98	103	123	121	370	227	176
July 5	105	110	129	123	348	225	177
July 6	115	117	135	130	323	222	175
July 7	127	127	144	138	303	219	176
July 8	136	133	148	143	280	217	175
July 9	146	139	152	148	259	212	173
July 10	155	145	156	153	243	210	172
July 11	168	153	162	158	230	205	170
July 12	181	159	168	163	225	203	170
July 13	198	168	175	170	220	203	169
July 14	210	177	179	174	206	199	168
July 15	237	187	184	181	215	198	168

[1] Input, 0.3025 foot of irrigation water during night of June 28–29.

At the United States Huntley (Mont.) Field Station, tensiometers were installed at two locations for the season of 1942: (1) In a plot of third-year alfalfa where the instruments were set at 12, 24, and 36 inches below the ground surface, and (2) in a plot of sugar beets where the instruments were set at the same depths. The soil at Huntley is a clay loam of recent alluvial origin. The subsoil contains layers of sand and gravel, which fill with water during the irrigation season. At the location of the tensiometer, an observation well that extended into a gravel stratum showed that the ground water in July stood at about 8 feet below the ground surface.

The tensiometers were set on May 20, 1942, and remained in position until September 20. The first crop of hay was cut on June 15. The data reported in table 2 relate to the period June 28 to July 25, during which the second crop of alfalfa was produced and the sugar beets were making vigorous growth. The alfalfa plot was irrigated on July 1, and the second crop of hay was cut on July 21.

The tensiometric record for the alfalfa plot shows that the plants used water from the root zone to the depth of 36 inches. The response to the irrigation of July 1 occurred sooner at 36 inches than at 12 inches, probably because this soil, when dry, shrinks to form deep cracks into which the irrigation water flows. At the 24-inch horizon, the lowest tension after the irrigation of July 1 was not reached until July 9. On July 21, when the second crop was cut, the tension at 12 inches was off the scale. At 24 inches, the tension went off the scale the next

TABLE 2.—*Observed tensions in the root zone of alfalfa and of sugar beets at the United States Huntley (Mont.) Field Station in 1942*

Date	Plot allocated to—							
	Alfalfa, 3d year, plot K–III–3				Sugar beets, plot K–III–6			
	Water input	Tension at indicated depth (inches)			Water input	Tension at indicated depth (inches)		
		12	24	36		12	24	36
	Foot	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Foot*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*
June 28	0.018	557	460	264	0.018	230	70	52
June 29		570	469	268		243	67	51
June 30		580	483	306	.683	298	71	54
July 1	.734	581	485	331		28		
July 2		398	470	21		37	31	22
July 3		82	437	30		53	40	27
July 4		44	394	47		66	45	30
July 5		51	316	52		82	45	32
July 6		67	257	60		102	49	34
July 7		77	210	63		122	49	37
July 8		93	195	69		150	54	40
July 9	.008	114	143	74	.008	176	54	43
July 10		136	210	77		213	55	44
July 11		162	266	81		254	57	44
July 12		200	342	90		308	61	47
July 13		241	407	97		358	63	49
July 14		284	441	105		400	66	53
July 15		332	465	114		435	70	57
July 16		376	469	120		451	68	54
July 17		434	487	137	1.008	482	73	60
July 18		483	503	162		82	38	22
July 19		519	503	182		28	40	29
July 20		544	516	216		50	45	34
July 21 [1]		[2]	520	253		64	47	36
July 22		[2]	[2]	283		84	49	38
July 23		[2]	[2]	293		108	51	40
July 24		[2]	[2]	298		130	51	43
July 25	.020	[2]	[2]	312	.020	161	58	48

[1] Alfalfa cut. [2] Tension off scale.

day, whereas at 36 inches it was still on the scale at the end of the period here reported. In fact, it was still on the scale (367 mm.) when the plot was irrigated on July 30.

The tensiometric record for the sugar-beet plot shows that the root zone of this crop was not as deep as that of alfalfa on this Huntley soil. The instruments at 24 and at 36 inches showed very little change of tension through the period here reported. In fact, through the whole season the highest tension observed at the 24-inch horizon was 83 mm. on August 25, when the instrument at 12 inches had been off the scale for 3 days and when the one at 36 inches also reached its highest tension (70 mm.).

The day-to-day conditions of tension in these two plots are shown in figure 1. The record, as charted in these graphs, extends from early June to mid-August 1942 and thus includes the period covered by the data in table 2. These graphs show that the alfalfa crop drew water freely from the root zone to the depth of 36 inches at least, whereas the sugar beets did not draw much water from the 24-inch horizon or below. One obvious consequence of this difference between the depths of the root zones of these crops is that the sugar beets had to be irrigated four times during the season, whereas the alfalfa was irrigated only twice. The sugar beets made normal, vigorous growth

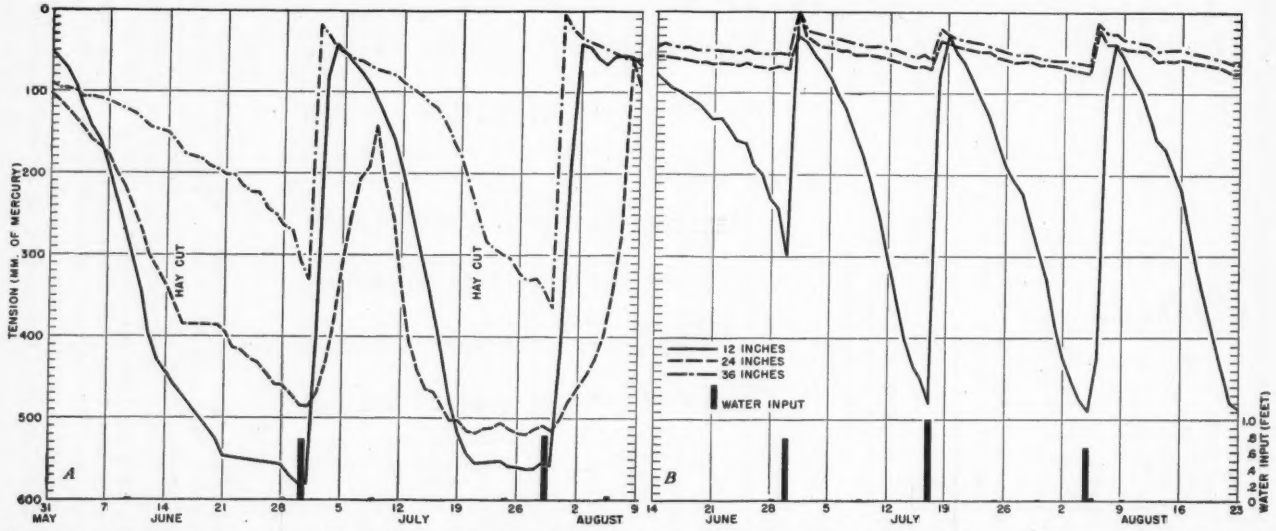

FIGURE 1.—Tensions from day to day at three successive depths in the root zone in plots of (*A*) alfalfa and (*B*) sugar beets, United States Huntley (Mont.) Field Station, 1942.

and yielded at the rate of 14.3 tons per acre. The alfalfa also grew well and yielded for three crops at the rate of 4.3 tons per acre.

The findings of 1942, that the active root zone for sugar beets was less than 24 inches deep and that the roots of alfalfa drew water from 36 inches and possibly below, led to a different series of settings in 1943. For that season, five instruments were set in the alfalfa plot at 6, 12, 24, 48, and 60 inches. The tensiometric data from this installation are shown in table 3. This record shows that the alfalfa roots drew some water from the 48-inch horizon but probably did not draw much, if any, from the 60-inch horizon.

TABLE 3.—*Observed tensions in the root zone of alfalfa and of sugar beets at the United States Huntley (Mont.) Field Station in 1943*

Date	Plot allocated to—										
	Alfalfa, 3d year, plot K-III-2						Sugar beets, plot K-III-5				
	Water input	Tension at indicated depth (inches)					Water input	Tension at indicated depth (inches)			
		6	12	24	48	60		6	12	18	24
	Foot	*Mm.Hg*	*Mm.Hg*	*Mm.Hg*	*Mm.Hg*	*Mm.Hg*	*Foot*	*Mm.Hg*	*Mm.Hg*	*Mm.Hg*	*Mm.Hg*
July 12	-------	391	532	172	162	90	-------	540	125	110	95
July 13	-------	-------	542	178	170	101	-------	-------	173	111	100
July 14	-------	572	543	180	175	105	-------	-------	202	115	100
July 15	-------	567	542	178	164	116	0.992	520	235	119	104
July 16	0.525	574	547	180	165	110	-------	22	2	22	10
July 17	-------	25	22	29	190	105	-------	40	28	50	43
July 18	-------	44	45	40	190	107	-------	61	53	60	50
July 19	-------	69	66	52	163	92	-------	79	66	64	57
July 20	-------	142	95	65	68	82	-------	105	80	70	65
July 21	-------	236	125	80	82	84	-------	148	97	75	65
July 22	.031	449	166	93	86	84	.031	220	107	79	70
July 23	-------	67	214	95	96	79	-------	161	63	75	69
July 24	-------	129	272	80	100	77	-------	224	125	87	75
July 25	-------	369	357	60	100	82	-------	259	142	101	83
July 26	-------	523	435	68	110	84	-------	406	164	105	92
July 27	.003	566	482	75	120	95	.003	420	173	107	84
July 28	-------	571	500	96	118	95	-------	461	164	102	88
July 29 [1]	-------	576	514	93	126	92	-------	469	213	112	94
July 30	-------	575	516	95	133	94	.716	479	224	137	100
July 31	-------	569	515	95	130	92	-------	15	15	14	14
Aug. 1	-------	544	502	91	110	87	-------	38	15	51	45
Aug. 2	.041	396	357	97	86	94	.041	57	29	62	50
Aug. 3	-------	24	439	99	118	88	-------	22	22	27	51
Aug. 4	.019	77	485	104	128	90	.019	39	29	62	55
Aug. 5	-------	27	507	107	130	90	-------	27	26	61	58
Aug. 6	-------	101	520	113	131	90	-------	52	33	71	61
Aug. 7	-------	309	527	111	134	92	-------	83	37	75	65
Aug. 8	-------	459	533	120	137	92	-------	125	46	83	72

[1] Alfalfa cut.

In the sugar-beet plot for the season of 1943 there were four tensiometers, set at 6, 12, 18, and 24 inches. The observations recorded in table 3 confirm the findings of 1942 for the 24-inch horizon, viz, that the sugar beets did not draw much water from that horizon. The highest tension reported for that depth in table 3 is 104 mm. on July 15, when the tension at the 6-inch horizon had been near the top of the scale for 4 days. The highest tension (115 mm.) during the whole season, for the 24-inch horizon, was on August 14, at which time the tension at 6 inches had been near the top of the scale for several days.

The range of tensions at the 18-inch horizon show that the sugar-beet roots were active to that depth in the Huntley soil.

At the United States Yuma Field Station, Bard, Calif., two sets of tensiometers were installed in plots allocated to wheat and to barley. These instruments were placed in the ground in December 1942 soon after the crops were seeded. They remained in place until late in the following April, when the crops were harvested. The soil at this station is sandy, with an admixture of river silt in the surface layer to the depth of 12 to 14 inches. The subsoil is sandy, with ground water at the depth of 5 to 6 feet. The instruments were installed in each plot at 7, 19, and 31 inches below the ground surface. The plots were nearly level; each was surrounded by a low border and irrigated by flooding.

TABLE 4.—*Observed tensions in the root zone of wheat and of barley at the United States Yuma Field Station, Bard, Calif., in 1943*

Date	Plot allocated to—							
	Wheat, plot C–I–15				Barley, plot C–II–15			
	Water input	Tension at indicated depth (inches)			Water input	Tension at indicated depth (inches)		
		7	19	31		7	19	31
	Foot	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Foot*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*
Mar. 7		(1)	124	72		(1)	156	85
Mar. 8	0.461	(1)	159	71	0.498	(1)	183	86
Mar. 9		33	41	46		279	78	63
Mar. 10		59	42	43		74	64	59
Mar. 11		80	51	47		93	62	58
Mar. 12		96	54	51		107	60	59
Mar. 13		122	56	53		129	62	61
Mar. 14		175	60	55		175	67	64
Mar. 15		305	62	56		257	68	65
Mar. 16		471	65	58		386	71	67
Mar. 17		565	68	60		492	74	70
Mar. 18		602	70	61		558	78	71
Mar. 19		(1)	75	63		604	84	74
Mar. 20		(1)	79	64		(1)	97	75
Mar. 21		(1)	83	65		(1)	136	78
Mar. 22		(1)	86	65		(1)	161	80
Mar. 23		(1)	95	65		(1)	204	81
Mar. 24		(1)	138	66		(1)	288	83
Mar. 25		(1)	195	67		(1)	315	85
Mar. 26		(1)	283	69		(1)	354	88
Mar. 27		(1)	332	70		(1)	378	90
Mar. 28		(1)	378	70		(1)	394	92
Mar. 29	.484	(1)	431	69	.555	(1)	407	94
Mar. 30		46	37	52		146	90	45
Mar. 31		71	46	48		66	58	50
Apr. 1		90	47	49		70	57	56
Apr. 2		110	53	50		82	66	60
Apr. 3		139	70	52		102	69	62

[1] Tension off scale.

The records for the two sets of tensiometers for 4 weeks ending April 3, 1943, are shown in table 4. Both plots had been irrigated on February 15. When the tabulated record began (March 7) both the instruments at 7 inches were off the scale. The tensions shown by the instruments at 19 inches indicated that the crops had begun to draw water from that horizon. Prior to the period covered by the

table there had been no evidence of the use of water from the 19-inch horizon, even though both the instruments at 7 inches had been off the scale prior to the irrigation of February 15. After the irrigation of March 8, the instruments at 7 inches showed a rapid increase of tension, reaching the top of the scale on March 19 and 20. The instruments at 19 inches showed relatively little increase in tension until after those at 7 inches had gone off the scale. Then they began a rapid rise, which continued until the next irrigation. The instruments at 31 inches showed very little change in tension throughout the period of the tabulated record. In fact, the complete record for the whole crop period, from December 19 to April 24, shows that the highest tension at the 31-inch horizon was 94 mm. This seems convincing evidence that the lower limit of the active root zone of these cereal crops in the Yuma soil was well above 31 inches.

At the Yuma Field Station, in the summer of 1943, tensiometers were installed in two plots of the Acala variety of cotton. The instruments were set at depths of 7, 19, and 31 inches. The cotton was planted the latter part of March, and the instruments were installed on May 1, when the plants were about 6 inches tall. The first flowers opened on June 3, and the first open boll was observed on July 20. The tabulated record (table 5) covers the 4 weeks from August 22, when the plants were fully grown and were fruiting heavily. This probably includes the period of the greatest use of water by the plants. It has been learned through long experience at the Yuma Field Station that cotton must be irrigated frequently if good yields are to be obtained. Irrigation water is usually available only once a week. After the first of July, if an irrigation is missed, the plants wilt in the afternoon after about 10 days. For example, plot C–I–21 was irrigated on June 29. It was not irrigated again until July 13, and the plants began to wilt on the afternoon of July 10. Plot C–II–16 was irrigated July 5, and the plants began to wilt on July 11 and wilted again each afternoon until the plot was irrigated on July 13. When these first wiltings occurred, the tensiometers at 7 inches were off the scale, but the instruments at 19 inches showed that the tensions were 57 mm. in plot C–I–21 and 78 mm. in plot C–II–16.

During the period of the records shown in table 5, the plots were irrigated each week with one exception. The record for each plot shows that the tension at the 7-inch horizon increased rapidly after each irrigation, whereas the increase was very small at both the 19-inch and the 31-inch horizons. In this respect, the data of the table are representative of the data for the whole season. Plot C–I–21 was not irrigated on September 13, after 1 week. The record shows that the manometer reached the top of the scale on September 15. It remained off the scale until the plot was irrigated on September 20, yet the continued low tensions at the 19-inch horizon indicate that the plants did not draw much water from that depth.

These tensiometric records, including the records for the whole season of 1943 and records from two other plots of cotton in 1944, show that on the Yuma station soil the active root zone of cotton was less than 19 inches deep. This finding makes it clear why it is necessary at that station to irrigate cotton 14 to 15 times during the season if good yields are to be obtained.

TABLE 5.—*Observed tensions in the root zone of cotton at the United States Yuma Field Station, Bard, Calif., in 1943*

Date	Plot allocated to—							
	Cotton, plot C–I–21				Cotton, plot C–II–16			
	Water input	Tension at indicated depth (inches)			Water input	Tension at indicated depth (inches)		
		7	19	31		7	19	31
	Foot	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Foot*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*
Aug. 22		415	78	60		498	75	63
Aug. 23	0.205	535	86	65	0.199	538	78	67
Aug. 24		40	48	43		38	44	62
Aug. 25		76	52	44		70	53	62
Aug. 26		108	56	50		105	60	61
Aug. 27		170	58	53		157	66	62
Aug. 28		322	60	56		278	70	65
Aug. 29		448	61	60		476	74	66
Aug. 30	.255	536	62	61	.205	574	77	67
Aug. 31		38	36	42		37	43	65
Sept. 1		70	42	47		62	52	63
Sept. 2		102	45	50		99	59	63
Sept. 3		171	48	55		151	65	63
Sept. 4		263	52	57		235	68	64
Sept. 5		372	53	60		387	73	65
Sept. 6	.273	456	56	63	.225	535	76	67
Sept. 7		30	25	46		41	41	60
Sept. 8		61	38	52		61	52	56
Sept. 9		91	41	55		93	60	57
Sept. 10		138	45	56		130	64	58
Sept. 11		211	49	61		190	67	60
Sept. 12		310	52	65		298	71	63
Sept. 13		395	54	66	.210	438	74	64
Sept. 14		468	55	67		32	42	57
Sept. 15		516	57	70		58	52	55
Sept. 16		(1)	60	72		86	58	56
Sept. 17		(1)	62	74		120	63	57
Sept. 18		(1)	66	77		174	66	60

[1] Tension off scale.

At the United States Scotts Bluff (Nebr.) Field Station, it was found by tensiometric observations during the season of 1942 that alfalfa used water freely to and including the 36-inch horizon. Because of this finding, the instruments installed in an alfalfa plot in 1943 were set at 12, 24, 48, and 72 inches. The soil here is classed as a very fine sandy loam. There is no ground-water table in proximity to the root zone. When the instruments were installed on May 26, the soil was dry to 6 feet or more and all the manometers rose nearly to the top of the scale. There were frequent showers between May 30 and June 16, and the plot was irrigated on June 10. These water inputs so reduced the tension that on July 1 the tension was 293 mm. at 12 inches, 258 mm. at 24 inches, 230 mm. at 48 inches, and 160 mm. at 72 inches. There was no effective rain for several weeks after July 1, and the tensions continued to rise at all four horizons until the plot was irrigated on July 20.

The tensiometric record for this alfalfa plot (table 6) for the 4 weeks beginning July 18 shows that the irrigation input of July 20 penetrated to the 48-inch horizon the following day and reached the 72-inch horizon about a week later. After the irrigation of July 20, the tensions rose rapidly at the 12-inch and 24-inch horizons and more slowly at the 48-inch horizon. There was little change at 72 inches.

After the period of the tabulated record the upward trend of tensions continued, notwithstanding a rain of 0.44 inch on August 20. By August 28 all the manometers, except that at 72 inches, were off the scale. The reading at 72 inches was 222 mm.

TABLE 6.—*Observed tensions in the root zone of alfalfa and of potatoes at the United States Scotts Bluff (Nebr.) Field Station in 1943*

Date	Plot allocated to—									
	Alfalfa, 2d year, plot K-I-10					Potatoes, plot K-I-11				
	Water input	Tension at indicated depth (inches)				Water input	Tension at indicated depth (inches)			
		12	24	48	72		12	18	24	36
	Foot	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Foot*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*	*Mm. Hg*
July 18		447	508	455	244		278	260	185	447
July 19		456	473	464	257		297	276	193	452
July 20	0.715	453	453	464	262		320	273	193	451
July 21		77	73	268	262		346	280	103	452
July 22	.009	92	84		270	0.009	363	255		
July 23	.012	97	93	321	275	.559	331	260	172	
July 24		107	98	428	277		92	85	75	
July 25		115	107	450	282		109	104	83	431
July 26		122	115	462	277		121	114	91	480
July 27 [1]		130	125	467	276		132	124	101	450
July 28		141	136	457	273		143	131	107	450
July 29		131	135	418			154	139	112	358
July 30		139	141	453			167	147	122	380
July 31		145	146	455	197		183	153	128	355
Aug. 1		152	154	454	201		205	161	136	331
Aug. 2		161	162	454	202		232	170	149	317
Aug. 3		170	171	405	208		257	170	159	311
Aug. 4		183	184	434	208	.247	306	187	176	307
Aug. 5		199	200	443	205		120	124	190	307
Aug. 6		217	213	447	196		125	119	153	308
Aug. 7		248	239	455	191		147	130	150	309
Aug. 8		286	272	446	185		169	140	153	304
Aug. 9		354	317	453	190		197	156	173	312
Aug. 10		417	390	444	187		233	169	194	298
Aug. 11		465	455	441	182		288	188	220	298
Aug. 12		479	481	443	187		354	207	253	303
Aug. 13		507	492	439	190		419	231	278	307
Aug. 14		499	506	456	191		415	281	316	316

[1] Alfalfa cut.

The alfalfa plot was irrigated on August 31 with 1.006 feet of water. This input reduced the tension immediately down to the 48-inch horizon and reached the 72-inch horizon on September 3. This review of the seasonal record of tensions shows that at Scotts Bluff the active root zone of alfalfa was deeper than 48 inches but probably did not extend to 72 inches.

The investigations at Scotts Bluff in 1943 included also an installation of four tensiometers in a plot allocated to potatoes. The instruments were set at 12, 18, 24, and 36 inches on July 3. The potatoes had been planted on June 12 and had emerged on June 29. The soil was dry when the instruments were set, particularly so at the 36-inch horizon. The instrument at 24 inches did not function well at first, and its record prior to the irrigation of July 23 may not be valid. The irrigation of that date (0.559 foot) penetrated immediately to 24 inches and reached the 36-inch horizon within a week. The light irrigation (0.247 foot) on August 4 penetrated to 18 inches, with

slight effect at 24 inches but none at 36 inches. The record for the whole season indicates that the active root zone of potatoes at Scotts Bluff extended to 24 inches or more but probably did not extend to 36 inches.

These examples of the tensiometric records from locations having a variety of different soils and a number of different crops show that the tensiometer makes available useful information regarding the depth of the root zone and the day-to-day changes that occur in the available soil water. The usefulness of such information is not confined to irrigated areas but is particularly valuable in any situation where irrigation water can be used when it is needed. In connection with agronomic investigations of many different sorts, it would be helpful to know from day to day the status of the available soil water. The observed differences of behavior between crop species or varieties may be associated with ranges in the depth of the root zone and consequently with the quantity of available soil water. The effects of differences in tillage practice or in weed control may be evaluated by observing the resulting differences in the quantity of available soil water. Moreover, in fertilizer experiments the crop yields often are so limited by the lack of available soil water at critical periods that the effects of the fertilizer treatments are not fully expressed.

QUANTITATIVE INTERPRETATION OF TENSIOMETRIC DATA

The measurement of the tension existing between the soil and its water yields useful agronomic information. But the question immediately arises: What does a given tension value mean in terms of the quantity of available soil water? It should be clearly understood that tension values are related only to the conditions of available soil water. The unavailable soil water, whether its quantity be large or small, has no effect on tension values.

There is an inverse relation between tension values and the quantities of available soil water. In other words, there is no measurable tension existing in a soil that is saturated with water. As the quantity of soil water decreases from the condition of saturation the tension increases. Thus it is obviously possible to establish the relation between the observed tension and the quantity of soil water by the simple expedient of determining, for any soil, the quantities of soil water that are associated with a series of observed tensions.

Exploration of this field of inquiry shows at once that, for any given soil, the tension value associated with any given quantity of available soil water is influenced by the apparent density of the soil. Thus, for any given soil with any given quantity of available water, the tension values decrease as the apparent density increases or as the soil becomes more compact. It is equally true that the apparent density of the soil is similarly related to the quantity of water required to saturate it. That is to say, as the soil becomes more compact less water is required to saturate it.

This relation between tension and apparent-density values makes it essential that in establishing, for field use, the relation between tension values and soil-water values, the sample of soil used should have the same apparent density and if possible the same "structure" as in the field.

In the investigations here reported, the objective has been to determine, for the soil of each location where tensiometers have been installed in the field, the relation between observed tension values and the quantity of available soil water. In the course of the investigation, three different procedures have been used: (1) The method of field sampling, (2) that of using soil cores in closed containers, and (3) that of using open containers with plants growing in the soil.

METHOD OF FIELD SAMPLING

By the method of field sampling, a number of tensiometers were set in a field and the tension values were observed and recorded daily. From time to time the soil was removed from the vicinity of one of the tensiometers to make it possible to obtain several samples from the soil immediately adjacent to the porous cup. On these soil samples, eight or more in number, the water content was determined by drying the soil to constant weight at 105° C., and the mean value for the soil water so determined was compared with the tension value observed just before the samples were taken. In the course of time, it was possible to obtain soil-water values corresponding to a fairly wide range of tension values.

The data of table 7 show the findings from a series of 24 such observations made in the plot at the Rubidoux Laboratory, in which there had been an installation of tensiometers since 1940. The entries are arranged in the order of the soil-water values, which range from 16.2 to 5.7 percent. The associated tension values range from 21 to 494 mm. The data of the table are shown also in figure 2. It is obvious, from both the table and the graph, that the points do not fall into a narrow path, but there is evidently an inverse relation between tension and soil water.

TABLE 7.—*Tension and soil-water values based on field sampling, plot U, Rubidoux Laboratory, December 1942 to April 1943*

Date	Tensiometer		Soil water	Date	Tensiometer		Soil water
	Depth	Reading			Depth	Reading	
	Inches	*Mm. Hg*	*Percent* [1]		*Inches*	*Mm. Hg*	*Percent* [1]
Jan. 13	12	21	16.2	Feb. 3	36	118	10.9
Jan. 16	12	58	14.4	Feb. 27	12	83	10.3
Jan. 14	12	40	14.2	Jan. 21	12	115	10.2
Jan. 29	12	51	13.8	Apr. 5	12	150	9.7
Jan. 18	12	68	13.7	Dec. 28	12	185	8.8
Jan. 29	12	78	13.4	Apr. 23	12	186	8.7
Feb. 26	12	45	13.4	Dec. 17	12	178	8.4
Feb. 26	12	54	12.8	Dec. 28	12	239	8.1
Feb. 27	12	63	12.0	Jan. 11	12	289	7.1
Jan. 18	12	88	11.9	Jan. 11	12	369	7.0
Feb. 27	12	67	11.7	Jan. 8	12	362	6.5
Jan. 18	12	65	11.6	Jan. 11	12	494	5.7

[1] Gravimetric.

While this method of field sampling affords direct information on the relation between tension and soil water, it has the following disadvantages: (1) It is not easy to obtain soil samples when the tension is at or close to zero; (2) it may take a long time to obtain representative samples related to a wide range of tensions; (3) slight differences in the character (particle size) of the soil at the different

locations or horizons may influence the quantity of total soil water but have much less influence on the quantity of available soil water, which is the part that influences the tension.

METHOD OF SOIL CORES

The method of soil cores in closed containers involved the use of steel cylinders, some 4 inches, and one 5 inches, in diameter and 5 to 6 inches long, fitted with tight covers. At the selected location and

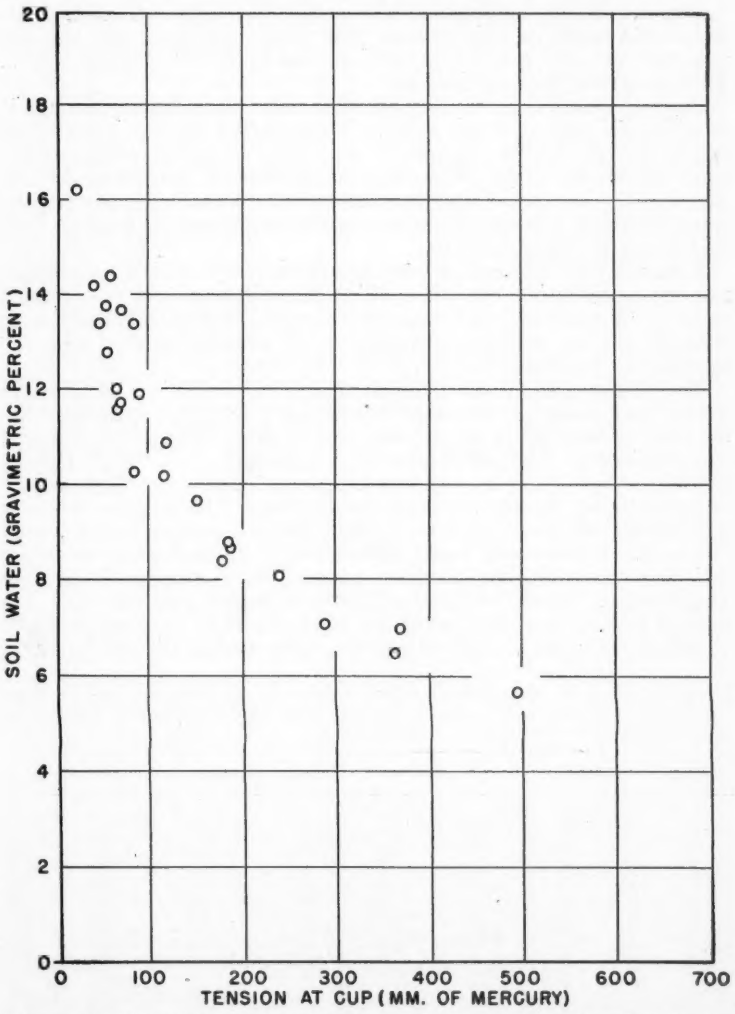

FIGURE 2.—The relation between tension and soil water as determined by the method of field sampling, plot U, Rubidoux Laboratory, Riverside, Calif.

depth, the cylinder was forced into the soil until the core of soil protruded above the top of the cylinder. Then the cylinder, with its soil core, was taken up; the core was cut off flush with the ends of the cylinder; and the metal covers, fitted with gaskets, were fastened in place. A tensiometer was installed with its porous cup near the center of the soil core. The whole system was weighed each day, and the tension was observed. When tensiometric equilibrium was attained, as indicated by no change in tension from day to day, a measured quantity of water was added and the resulting change in tension was observed. When equilibrium of tension was again attained, more water was added. This process was continued until the soil approached saturation and the tension stood at zero or slightly above. This completed the sorption run.

The soil was then aerated by drawing a stream of dry air through it to remove a portion of the water. The aeration apertures were then closed, and the tension was observed each day until it remained constant for several days. Then another portion of the soil water was removed by aeration. This process was continued until the tension reached equilibrium near the upper end of its measurable range. This completed the desorption run.

Each soil core was put through one or more cycles, i. e., a sorption run and a desorption run, after which the apparatus was taken down and the soil was dried to determine its mass. It was then possible to compute the successive percentages of soil water associated with the equilibrium tensions.

The data in table 8 show the successive values for the equilibrium tension and the soil water observed with a core of soil from near the tensiometer location in the orchard plot at the Rubidoux Laboratory. Observations on this core of soil were begun on April 8, 1943. During the first month, the core was aerated and dried down to 5.94 percent of water before the sorption run was started. The sorption run was continued until two successive equilibrium tensions of 18 mm. were observed. It has been found difficult with the soil cores to attain satisfactory equilibrium tensions at zero with diurnal changes in temperature. Upon completion of the sorption run, the soil was aerated by a method that permitted the removal of a known quantity of water each time. This desorption run was continued until an

TABLE 8.—*Tension and soil-water values obtained by the use of a closed container with a core of soil 9 to 15 inches in depth from plot U, Rubidoux Laboratory, experiment 59–5, June 1943 to January 1944*

Date	Tension	Soil water		Date	Tension	Soil water	
	Mm. Hg	*Grams*	*Percent*		*Mm. Hg*	*Grams*	*Percent*
June 10	242	603	7.38	Sept. 22	75	1,174	14.37
June 18	146	722	8.84	Sept. 29	87	1,118	13.68
June 23	100	840	10.28	Oct. 7	93	1,082	13.24
July 1	73	961	11.76	Oct. 12	103	1,028	12.58
July 5	52	1,078	13.19	Oct. 20	111	963	11.79
July 13	40	1,203	14.72	Oct. 26	126	898	10.99
July 21	29	1,324	16.21	Nov. 4	153	810	9.91
July 28	18	1,448	17.72	Nov. 10	177	754	9.23
Aug. 12	18	1,508	18.46	Nov. 18	246	664	8.13
Aug. 20	26	1,470	17.99	Dec. 2	343	595	7.28
Aug. 27	32	1,440	17.63	Dec. 14	491	531	6.50
Sept. 2	37	1,406	17.21	Dec. 27	624	492	6.02
Sept. 9	52	1,312	16.06	Jan. 10	469	523	6.40
Sept. 15	65	1,241	15.19	Jan. 20	365	553	6.77

equilibrium tension of 624 mm. was attained when the soil water was at 6.02 percent, after which water was added twice in small quantities to obtain points on the sorption path below those of the first run.

The data of table 8 are plotted in figure 3. From this graph it will be seen that for any given soil-water value the tension value is lower for the sorption run than for the desorption run. Such differences have been observed with all the soil cores used in these investi-

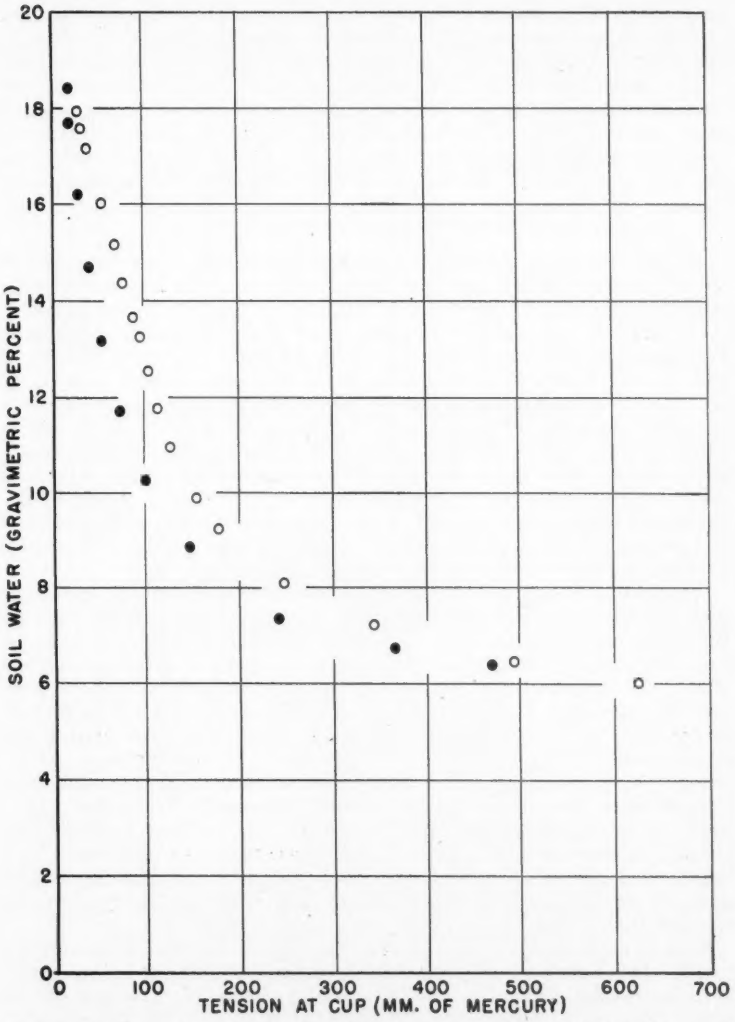

FIGURE 3.—The successive points of the sorption run (black circles) with a soil core in a closed container and of the desorption run (open circles) on the same core. Plot U, depth 9–15 inches, Rubidoux Laboratory, Riverside, Calif.

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gations. Whether these differences are due to failure to attain true equilibrium between changes in soil water or to inherent characteristics of the soil has not been determined.

The methods involving the closed container yield a series of points that are acceptably consistent not only for each core but also between several cores from the same location. But the fact that the point path of the sorption run does not coincide with that of the desorption run makes for uncertainty as to which of the two is the more acceptable. The method has two other disadvantages: (1) It takes several months to complete a full cycle of observations, and (2) there is uncertainty as to when the condition of saturation has been attained.

The data here reported for the soil core in the closed container may be compared with those reported for the method of field sampling (table 7 and fig. 2). This comparison is justified because both experiments involved soil from the same plot. It will be seen that, considering the random nature of the observations, the agreement is good.

METHOD OF OPEN CONTAINERS

With the method employing open containers with plants growing in the soil, several different sizes of containers were used. The largest were iron pails 32 cm. deep by 28.5 cm. in diameter, with a volume capacity, to 3 cm. below the rim, of 18.5 liters, or of 27 to 28 kg. of dry soil. The smallest containers were 25 cm. in diameter and deep enough to hold 10 cm. of soil to 2.5 cm. below the rim; these held 7 to 8 kg. of dry soil. The container was provided with an input tube of small diameter, discharging at the center of the bottom, to the outer end of which a glass tube with stopcock was attached to control the water input and to serve as an indicator of the water level in the saturated soil. In the earlier experiments, a layer of gravel was placed in the bottom of the container to aid the distribution of water. This proved to be a source of error because of the free water held in the gravel during the early part of a run.

A tensiometer support was attached to the side wall of the container with the porous cup placed near the center of the soil mass (fig. 4). When the soil was placed in the container, its mass and water content were determined, it was packed to approximately the apparent density of its field condition, and its volume was subsequently measured from time to time as a check on changes in apparent density. The several components of the apparatus were weighed, so that by weighing the whole system from day to day the quantity of soil water could be computed. Seedling plants of alfalfa, grass, or clover were started in the soil when the apparatus was set up. The water was added either from below through the input tube or by surface applications. Usually, water was added until the soil was saturated and the observed tension was at or near zero; it was then withheld until the plants had used all or nearly all the available water. The period required to exhaust the available water is referred to as a run.

This method was found the most acceptable of the 3 methods investigated. It is not free from certain idiosyncrasies due in part to effects of temperature changes in the soil and in part to the position of the porous cup of the tensiometer in the soil in relation to the zone of most active root absorption. But after an apparatus has been set up and the plants are well grown, a run may be made in a week or 10 days

and repeated often enough to afford an acceptable assemblage of data and opportunity to observe the nature and extent of the changes in the relation between tension and soil-water values that occur with the evolution of soil structure consequent upon the repeated wetting and drying and the action of plant roots. More than 20 consecutive runs have been made with some soil samples, and it has been found

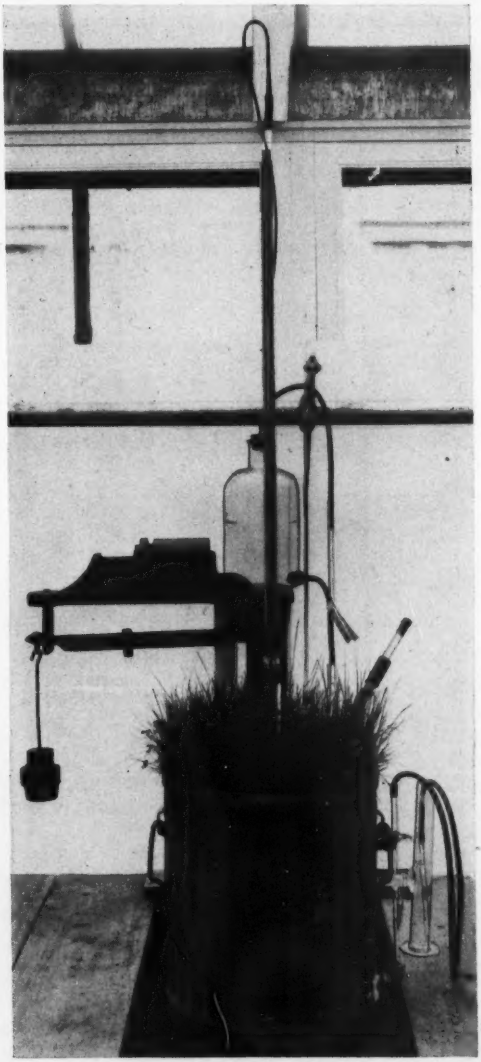

FIGURE 4.—A container used for the tensiometric calibration of soil.

that after the first few runs there is good agreement among the successive point paths.

The findings on one soil, as calibrated in an open container, are shown in table 9 and illustrated in figure 5. There were 24 successive runs made with this soil. Several of these runs were continued beyond the range of the tensiometer until the plants wilted. Wilting occurred at various levels of soil water, depending upon the rate at which water

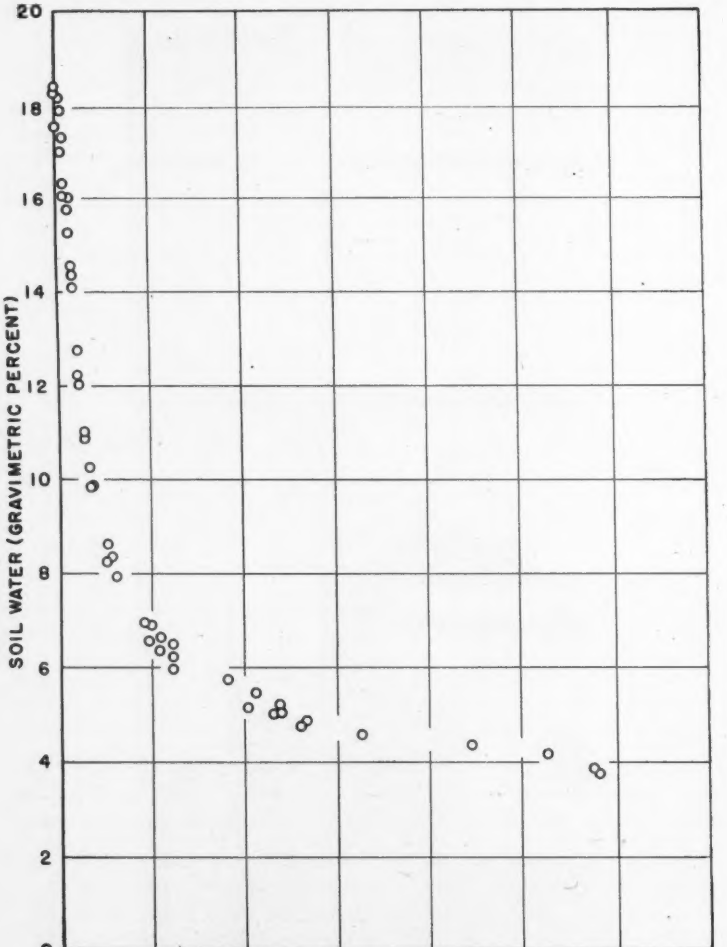

FIGURE 5.—The relation between tension and soil water with Lanham (Md.) soil, observed during three successive runs, Nos. 22–24, in an open container with perennial ryegrass and white clover.

was used by the plants. The range of soil-water percentages at the onset of wilting in 6 of the runs was from 3.20 to 3.86.

It will be seen in figure 5 that the points for the three runs fell into a narrow path forming a curve. This curve starts at approximately 18 percent and zero tension and ends at approximately 4 percent at the highest measurable tension. After the soil from a given field location in which tensiometers were installed has been calibrated, the curve that best fits the plotted point path serves as a frame of reference for converting observed tension values into the corresponding soil-water values.

TABLE 9.—*Tension and soil-water values for 3 successive runs, Nos. 22–24, Lanham (Md.) soil, February 5 to March 18, 1944*

Run 22		Run 23		Run 24	
Tension	Soil water	Tension	Soil water	Tension	Soil water
Mm. Hg	*Percent*	*Mm. Hg*	*Percent*	*Mm. Hg*	*Percent*
0	18.49	0	17.54	0	18.35
5	18.20	6	17.03	6	17.91
8	17.32	10	16.07	9	17.32
14	15.78	13	15.27	14	16.00
17	14.54	17	14.10	18	14.32
28	11.03	21	12.27	21	12.78
36	9.89	26	10.88	23	12.05
56	8.32	33	9.86	33	10.26
97	6.93	50	8.25	38	9.57
120	6.49	96	6.56	50	8.61
181	5.76	106	6.34	61	7.96
210	5.47	121	5.98	91	6.96
236	5.20	201	5.17	107	6.64
442	4.37	230	5.03	120	6.20
524	4.15	260	4.80	237	5.10
573	3.86	-------	2.98	264	4.88
				324	4.59
				578	3.78
				-------	3.39

THE CURVE EQUATION

After several trials, it was found that the equation

$$y=\frac{b}{x+a}-c,$$

where y=the water content, x=the tension, and a, b, and c are constants for the particular soil, seemed to give a satisfactory fit for the observations. The curve plotted by means of this equation is a hyperbola in which the value of y approaches the value of c as x increases beyond the limit of measurement. The value of c appears to represent an important characteristic of the soil, i. e., the unavailable water, which is the quantity of water that cannot be removed by any tension, however large. The equation was chosen empirically because it appeared to describe the conditions better than any other tried. It is not known to have any theoretical justification.

The method of evaluating the curve-equation constants may be illustrated by using the data from a calibration run made by the open-container method with a sample of composited surface soil, 0–8 inches, from a field in the South Farm at the [U. S.] Plant Industry Station, Beltsville, Md. For this soil, the record of the first run is

shown in table 10 and the data are plotted in figure 6. In this experiment the tension scale was graduated in units of centimeters of water instead of millimeters of mercury.

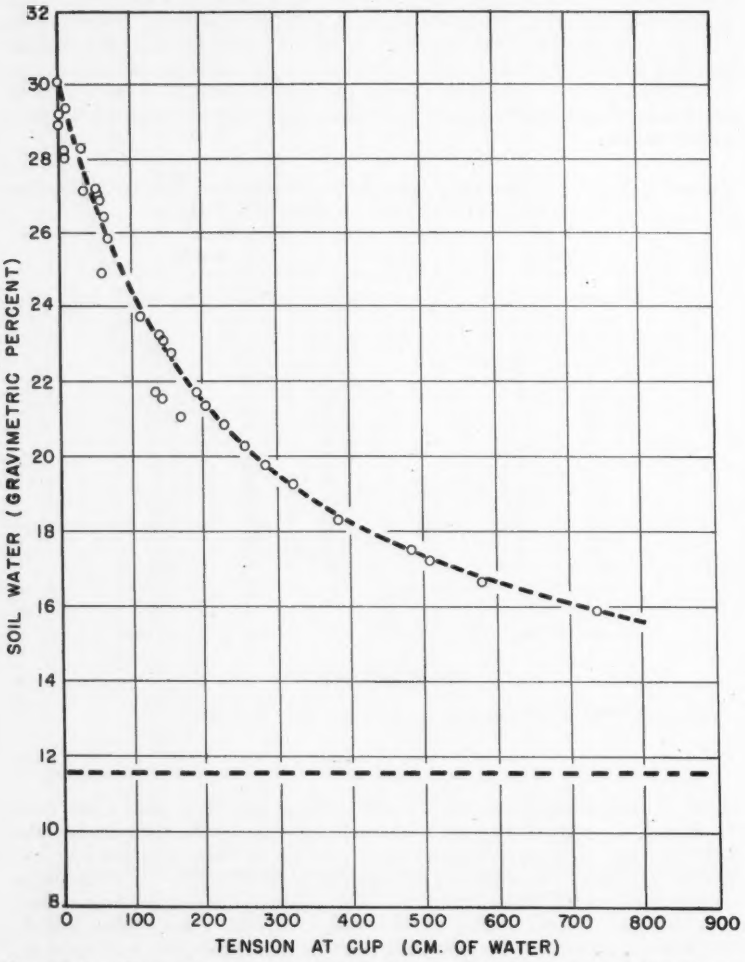

FIGURE 6.—The relation between tension (cm. water) and soil water, in Beltsville (Md.) silt loam, observed during the first run in an open container with orchard grass. The line at the soil-water ordinate 11.6 is at the lower limit of the available soil water.

TABLE 10.—*Tension and soil-water values for Beltsville (Md.) silt loam, first run, July 10, 1944*

[Observations made between 8 a. m. and 4:45 p. m.]

Date	Clock time	Input	Daily loss	Tension	Soil water	
		Grams	*Grams*	*Cm. H_2O*	*Grams*	*Percent*
July 10	2:55	2,114		0	2,272	30.10
July 11	8:50			14	2,214	29.33
	1:00			3	2,204	29.20
	4:15			3	2,186	28.96
July 12	8:10		78	33	2,136	28.30
	1:00			10	2,129	28.21
	3:55			10	2,115	28.02
July 13	8:07		85	51	2,051	27.17
	12:45			50	2,048	27.13
	4:20			55	2,040	27.03
July 14	8:12		19	59	2,032	26.92
	4:45	43		34	2,049	27.15
July 15	8:15		79	65	1,996	26.44
	3:45	7		70	1,954	25.89
July 16	[1]		123			
July 17	8:00		123	139	1,757	23.28
	10:35	213		143	1,748	23.16
	4:40			61	1,881	24.92
July 18	8:12		176	114	1,794	23.77
	4:32			154	1,715	22.72
July 19	8:15		155	190	1,639	21.71
	12:54			201	1,612	21.36
	4:15			227	1,573	20.84
July 20	8:05		111	254	1,528	20.24
	4:32			282	1,491	19.75
July 21	8:07		75	320	1,453	19.25
	4:22	331		382	1,383	18.32
July 22	8:15		143	131	1,641	21.74
	12:30			143	1,626	21.54
	3:30			169	1,586	21.01
July 23	[1]		160			
July 24	8:09		160	482	1,321	17.50
	12:53			505	1,302	17.25
	4:21			578	1,259	16.68
July 25	8:13		118	734	1,203	15.94

[1] Sunday.

The three pairs of values chosen for use in the computation follow:

x	y	
0	30.10	(1)
201	21.36	(2)
734	15.94	(3)

After the values for x and y have been selected, the values for a, b, and c may be obtained by the method of simultaneous equations. But it has been found that the essential computations may be made more expeditiously with a calculating machine as follows: [5]

Let:

$x_1y_1 = \text{I}$
$x_2y_2 = \text{II}$
$x_3y_3 = \text{III}$
$x_1 - x_2 = \text{IV}$
$x_2 - x_3 = \text{V}$
$y_1 - y_2 = \text{VI}$ and
$y_2 - y_3 = \text{VII}$

[5] The author is indebted to Francis Scofield for suggesting the use of the equation and for devising the method here shown for evaluating the constants.

Then:

$$c=\frac{(\text{II}-\text{I})\ (\text{VII})-(\text{III}-\text{II})\ (\text{VI})}{(\text{IV})\ (\text{VII})-(\text{V})\ (\text{VI})}=-11.62$$

$$a=\frac{\text{II}-\text{I}}{\text{VI}}-\frac{(\text{IV})}{(\text{VI})}\,c=224 \text{ and}$$

$$b=(y_1+c)\ (x_1+a)=4{,}140$$

From these computations it will be found that the value for c has a negative sign, whereas the values for a and b are positive. The curve equation for this run of this soil thus becomes:

$$\text{Total soil water}=\frac{4{,}140}{x+224}+11.62 \text{ or}$$

$$\text{Available soil water}=\frac{4{,}140}{x+224}$$

The curve yielded by the equation in the scale of total soil water is shown in figure 6, as is also the ordinate representing the $-c$ value, or the lower limit of the available soil water.

The points on the graph that fall below the curve represent observations that were made soon after the soil was watered on July 17 and again on July 21. These show that tensiometric equilibrium was not immediately attained after the water was added. The graph also shows, in the low-tension range, the effects on the observed tension of the diurnal changes of temperature in the soil. A rise in soil temperature when the soil is very wet may cause a decrease of tension. This phenomenon is less noticeable, or does not occur, when the soil becomes drier.

It is to be expected that, with successive runs on the same soil sample, changes in the water relations will occur as the soil becomes more compact and as the structure evolves. In the case of the Beltsville silt loam referred to above, the second run had its zero tension at 29 percent of water, whereas for the third and later runs it held 28 percent or slightly less at zero tension. For each of these later runs, the soil-water values when the upper limit of tension was reached were approximately the same as for the first run.

When, after several runs, the changes in the plotted-point path become inconsequential, it may be assumed that the relations then shown between tension and soil water are approximately the same as those existing in the field. At this time, a new set of x and y values may be chosen for the final evaluation of the curve-equation constants. The curve obtained with these values may then be superimposed on the plotted points for each of the runs to test its acceptability.

Because the values obtained for the constants depend upon the x and y values of the three points selected, it is well to use care in their selection. If data are available from several successive runs of the same soil or from runs with two or more containers of the same soil, the x and y values to be used in the computation may be obtained by the method of harmonic means. If data are available from only one run, such as with a soil core, the points may be evaluated by the method of least squares. But these latter calculations are tedious and may not be warranted. If the data are plotted carefully, it is not difficult to select three points that give a curve of acceptable fit for

any one run, or if there are several runs the harmonic means of points in the same range should be used.

The construction of a comparison curve and the testing of its fit to a series of observed points is facilitated by computing the data for a table to show the soil-water values for a series of tension values. Such a table for the Beltsville loam is here shown (table 11). In this table the values for available soil water and for total soil water are both given. If it is desired to test critically the fit of a computed curve to the data of a run, this may be done by using in such a table the observed tension values and then comparing the computed soil-water values with the observed values.

TABLE 11.—*Computed soil-water values for curve construction, Beltsville silt loam (composite), run of July 10, 1944*

Tension (cm. H_2O)	$x+a$	Available soil water $\left(\frac{b}{x+a}\right)$	Total soil water $\left(\frac{b}{x+a}-c\right)$	Tension (cm. H_2O)	$x+a$	Available soil water $\left(\frac{b}{x+a}\right)$	Total soil water $\left(\frac{b}{x+a}-c\right)$
		Percent	*Percent*			*Percent*	*Percent*
0	224	18.48	30.10	350	574	7.21	18.83
25	249	16.62	28.24	400	624	6.63	18.25
50	274	15.11	26.73	450	674	6.14	17.76
75	299	13.84	25.46	500	724	5.72	17.34
100	324	12.78	24.40	550	774	5.35	16.97
150	374	11.07	22.69	600	824	5.02	16.64
200	424	9.76	21.38	700	924	4.48	16.10
250	474	8.73	20.35	800	1,024	4.04	15.66
300	524	7.90	19.52				

CONVERSION TABLES

Upon the completion of the tensiometric calibration of the soil samples from a field location in which tensiometers have been installed, the next step is to set up a conversion table. It is quite possible to convert each reported tension value into its soil-water equivalent by direct computation, but in the long run the use of a conversion table saves time and diminishes the chances of error. It is no small task to construct a conversion table containing soil-water values for each of the 600 or 800 units of the tensiometer scale. For that reason, it is appropriate to give the subject careful advance consideration.

A conversion table may be made to show for each tension unit (1) the gravimetric values for total soil water, (2) the gravimetric values for available soil water, or (3) the volumetric values for available soil water. Which of these three should be used for any given situation is a question that merits serious consideration.

For use in connection with irrigation operations where the depth of water input may be measured and is usually reported in terms of feet, it has been found that the conversion table with the volumetric values for available soil water is the most convenient. Volumetric soil-water values may be computed from gravimetric soil-water values by multiplying the latter by the value for the apparent density of the soil. Thus, if for a certain tension the gravimetric soil-water value is 12 percent and the apparent density of that soil is 1.52, the volumetric soil-water value is 18.24 percent. Furthermore, a volumetric soil-water value of 18.24 percent is equivalent to 0.1824 foot of water in each foot of soil.

The operations involved in constructing a conversion table, which are at best laborious, may be lightened appreciably by substituting for the equation $y=\frac{b}{x+a}-c$, another equation, namely, $v=\frac{w}{ex+1}$, in which w=the total available soil water, e=the reciprocal of the curve-equation constant a, x=the tension, and v=the available soil water at the given tension. If it is desired to tabulate the values for total soil water, this may be done by adding to the value for v the value for the curve-equation constant $-c$.

EVALUATING THE WATER-HOLDING CHARACTERISTICS OF SOILS

The findings obtained from the tensiometric calibration of a sample of soil may serve as useful criteria for evaluating the water-holding characteristics of the soil. The calibration yields three important criteria: (1) The quantity of the total available soil water, for which the symbol w is used; (2) the quantity of the unavailable soil water, for which the symbol $-c$ is used; and (3) the factor e, which indicates the nature of the energy relations existing between the soil and its available water. The factor e is evaluated from $e=\frac{1}{a}$. Thus, the water-holding characteristics of the Beltsville silt loam herein reported on may be evaluated as follows:

w=18.48 percent (gravimetric)
$-c$=11.62 percent (gravimetric)
e= .0045, when the tension scale is in centimeters of water

If the tension scale were in millimeters of mercury, the value for e would be $0.0045\times1.35=0.0061$.

For the three soils used as examples in this report, the water-holding characteristics may be described concisely as follows:

Soil:	*Available soil water* (w) (*percent*)	*Unavailable soil water* ($-c$) (*percent*)	*Value* (e) (*mm. Hg*)
Rubidoux sandy loam, plot U	17. 30	4. 31	0. 0156
Lanham (Md.) sandy soil	15. 70	2. 70	. 0234
Beltsville (Md.) silt loam	18. 48	11. 62	. 0061

It will be seen, from the nature of the equation in which the factor e is used, that its value determines the shape of the curve. The relations are such that the higher its value the more pronounced is the bend of the curve.

SUMMARY AND CONCLUSIONS

To serve the purposes of agronomic investigations, it is convenient to recognize two categories of soil water, viz, available and unavailable. It is only the available soil water that is useful to plants or is free to move through the soil.

There are currently in general use three methods of measuring the quantity of water in the soil at any given time: (1) The gravimetric method, in which soil samples are weighed and dried to constant weight, and from the loss of weight the water content is computed; (2) an electrometric method, involving the measurement of the electrical resistance between two electrodes embedded in a block of gypsum placed in the soil; and (3) the tensiometric method, which

involves the measurement, with a mercury manometer, of the tension existing between the soil and its water.

In the first part of the investigation reported here, it was found that the tensiometer yielded precise and useful information on the status of the available soil water at any given horizon of the root zone throughout a range extending from the condition of saturation to that resulting from the withdrawal of 80 to 90 percent of the available soil water. The findings indicate that the instrument is highly sensitive to changes in the quantity of available soil water; that it gives consistent, dependable, and reproducible information; and that it is not greatly influenced by differences in soil or atmospheric temperatures or in the salinity of the soil solution. Thus, just as a thermometer may be used to show the temperature of the soil or of the air, so the tensiometer may be used to show the status of the available water in the soil.

This paper includes detailed reports of tensiometric observations at a number of field locations with a number of different crops. These observations show the changes in tension that occur from day to day at successive depths in the soil in response to, and following, inputs of water. They show also that the depth of the active root zone differs greatly between different crops grown on adjacent plots of the same soil.

In the second part of the investigation, it was found that it is possible to establish an acceptable relation between the data of tensiometric observations at any given field location and the quantity of available soil water at that location. This finding makes it possible to make up, for the soil of any given field location, a conversion table by the use of which the data of tensiometric field observations may be translated into (1) equivalent gravimetric percentages of available soil water, (2) equivalent volumetric percentages of available soil water, or (3) equivalent gravimetric or volumetric percentages of total soil water. Several methods of procedure to this end have been explored, and three of these methods are described.

The method of field sampling involves taking a number of soil samples from the area immediately adjacent to the tensiometer cup and comparing the tension reading with the mean value for total soil water as determined by drying the samples.

The method of soil cores in closed containers involves a series of successive changes in the quantity of water in the core with observations as to the tension after each change.

The method of open containers with growing plants involves a series of runs, for each of which the soil in the container is saturated, and the tension is observed and the weight of the system is recorded frequently as the plants absorb and transpire the soil water.

Of these three methods, the last-named yielded the most complete and acceptable assemblage of comparative data. When the findings from any one of the methods are plotted on coordinate paper, the path of the points forms a curve starting from zero tension, when the soil is saturated, and ending at some lower water percentage, when the upper limit of measurable tension is reached.

It has been found that the path of the points as plotted may be fitted with a curve computed by the use of the equation $y=\frac{b}{x+a}-c$, in

which x=the tension value; y=the soil-water value; and the constants a, b, and c are evaluated for each soil from three pairs of the values for tension and soil water. The value of $-c$ represents the quantity of unavailable water.

The evaluation of the curve-equation factors may also serve as a basis for a concise and precise description of the water-holding characteristics of the soil that has been used for tensiometric calibration. This in turn makes it possible to classify the soils of any location or the successive sections of the soil profile at any location, into categories that are delimited by their water-holding characteristics.

INHERITANCE OF RESISTANCE TO BUNT (TILLETIA CARIES) IN HYBRIDS WITH TURKEY WHEAT SELECTIONS C. I. 10015 AND 10016[1]

By ALI A. EL KHISHEN, former *graduate student, University of California,* and FRED N. BRIGGS, *agronomist, California Agricultural Experiment Station*

INTRODUCTION

Studies of the inheritance of resistance in wheat to bunt (*Tilletia caries* (DC). Tul.) made at this station (*1, 2, 3, 4, 8*)[2] have demonstrated the existence of four major genetic factors for resistance to this disease. These factors, named for the variety in which they were discovered, are the Martin, Hussar, Turkey, and Rio factors. Briggs (*4*) has shown linkage between the Martin and Turkey factors with a crossover value of 34.22 percent. Stanford (*8*) found a close linkage between the Rio and Turkey genes with a recombination value of 2.4 percent.

As soon as a gene for resistance to bunt is discovered, it is used in test crosses with new varieties under study for the purpose of identifying their genes. When the present study was undertaken, Stanford (*8*) had not yet discovered the Rio gene; therefore the crosses with Rio were made at a later date and the data were obtained after Dr. El Khishen returned to Egypt. As will be seen later, this information has been very useful in the genetic analysis of Turkey 10016.

MATERIALS AND METHODS

The resistant parent varieties, Turkey C. I.[3] 10015 (Selection No. 4300) and Turkey C. I. 10016 (Selection No. 4319) are 2 of the 12 resistant lines isolated by Kiesselbach and Anderson (*5*) from Turkey (South Dakota 144) wheat. Other of their lines showed various amounts of bunt up to more than 90 percent. Turkey 10016 was found to have a higher level of resistance than Turkey 10015, and this has also been the case at the California station (table 1).

The two resistant varieties Turkey 10015 and Turkey 10016 were crossed with susceptible Baart, with the four tester varieties Martin (*MM*), Selection 1403 (*HH*), Turkey 3055 (*TT*), Rio (*RR*), and with each other.

The seeds for producing the F_1 and F_2 generations were treated with copper carbonate to prevent bunt infection which would lead to differential elimination of susceptible lines as well as some heterozygous plants in F_2. Since some genetically susceptible plants may escape infection, and some resistant plants may become diseased, the F_2 provides inadequate information; therefore the F_3 populations were used for the genetical analyses. Some rows of F_2 plants were grown with the F_3 to obtain an indication of the amount of bunt to be expected in F_3 rows arising from fully heterozygous F_2 plants.

All seeds used for the bunt nursery were thoroughly inoculated with bunt spores propagated on White Federation for that purpose.

[1] Received for publication April 22, 1944.

[2] Italic numbers in parentheses refer to Literature Cited, p. 413.

[3] C. I. denotes accession number of the Division of Cereal Crops and Diseases, Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture.

This collection of *Tilletia caries*, designated by Reed (*6*) as physiologic race III and by Rodenhiser and Holton (*7*) as T–1, has been used in all the smut studies at this station.

The seeds were spaced about 2 inches apart in rows 1 foot apart. The seeds were planted in November and harvested the following May and June. The number of plants per row averaged about 55. At harvest the plants were pulled and classified as smutted or disease-free. Plants which showed any of the disease were placed in the smutted class.

TABLE 1.—*Annual percentages of bunt infection in the parent varieties grown at Davis, Calif., 1933–43*

Year	Bunt infection (percent) on—						
	Baart	Turkey 10015	Turkey 10016	Martin	Selection 1403	Turkey 3055	Rio
1933	66.0	4.3	0	0	0	0.1	0
1934	84.4	4.5	.7	0	1.4	.3	.4
1935	82.2	8.8	0	0	1.7	0	1.1
1936	72.9	3.8	0	0	0	1.8	.2
1937	68.1	4.2	2.1	0	.9	1.0	.8
1938	54.0	.4	0	0	0	0	.2
1939	93.5	.7	.5	0	0	.7	.4
1940	89.7	3.6	.9	0	0	2.1	1.2
1941	45.4	0	0	0	0	0	0
1942	60.0			0	0	1.3	0
1943	77.7	3.9	.2	0	0	2.3	1.2
Average	72.2	3.4	.4	0	.4	.6	.5

EXPERIMENTAL RESULTS

Conditions were generally favorable for bunt development as shown by the level of infection in the Baart check rows and by the upper range of the homozygous susceptible rows. For convenience the data from hybrids involving Turkey 10015 and Turkey 10016 will be considered separately, although they appear in the same table.

INHERITANCE OF RESISTANCE TO BUNT IN HYBRIDS WITH TURKEY 10016

The F_3 data are given in table 2. Since these data are of importance principally as they relate to F_3, they will be discussed in connection with the F_3 data presented in table 3. There were 221 F_3 rows of Turkey 10016 × Baart with 2 Baart and 1 Turkey 10016 rows for about every 25 F_3 rows. The average infection of Turkey 10016 was 0.5 percent and for Baart 93.5 percent.

TABLE 2.—*Percentage of bunted plants in F_2 of 11 crosses at Davis, Calif.*

Year grown	Cross	Total plants	Bunted plants	
		Number	*Number*	*Percent*
1939	Turkey 10016 × Baart	1,734	356	20.4
1939	Turkey 10016 × Martin	2,277	45	1.9
1939	Turkey 10016 × Selection 1403	1,801	65	3.6
1939	Turkey 10016 × Turkey 3055	2,462	12	.5
1943	Turkey 10016 × Rio	660	1	.01
1939	Turkey 10015 × Baart	2,107	896	42.5
1939	Turkey 10015 × Martin	2,186	85	3.9
1939	Turkey 10015 × Selection 1403	1,949	187	9.6
1939	Turkey 10015 × Turkey 3055	2,378	59	2.5
1943	Turkey 10015 × Rio	150	11	7.3
1940	Turkey 10015 × Turkey 10016	592	13	2.2

TABLE 3.—*Distribution of F_3 rows of the crosses named into 5-percent classes for bunt infection; Davis, Calif.* [1]

Cross	Distribution of rows by 5-percent classes																				Total number of rows
	0	1–5	5–10	10–15	15–20	20–25	25–30	30–35	35–40	40–45	45–50	50–55	55–60	60–65	65–70	70–75	75–80	80–85	85–90	90–95	95–100	
Turkey 10016 × Baart	28	25	8	14	20	29	24	10	9	6	6	7	7	5	5	6	5	2	5			221
Turkey 10016 × Martin	145	54	24	13	5	3	4	0	0	1	0	1										250
Turkey 10016 × Turkey 3055	206	35	8	1																		250
Turkey 10016 × Rio	218	31	1																			240
Turkey 10016 × Selection 1403	106	52	25	13	14	9	9	6	4	4	0	1	2	0	1	0	1	0	1			248
Turkey 10015 × Baart	4	13	13	10	9	9	7	6	9	18	13	18	10	10	10	13	17	6	16	13	2	226
Turkey 10015 × Martin	93	56	43	22	9	6	10	2	2	1	1	3	0	0	0	0	1					249
Turkey 10015 × Turkey 3055	95	96	39	14	7	3	6	1	1	1												263
Turkey 10015 × Rio	37	79	48	35	14	8	5	3	1	2	1	0	1									234
Turkey 10015 × Selection 1403	77	36	23	29	12	10	11	5	8	11	2	4	2	2	4	3	1	3	1	2		246
Turkey 10015 × Turkey 10016	179	39	22																			240

[1] The cross between Turkey 10015 and Turkey 10016 was grown in 1940. The crosses involving Rio were grown in 1943. All others were grown in 1939. The behavior of the parents and Baart during these years is shown in table 1.

Figure 1 shows the distribution of the F_3 rows on the basis of 5-percent classes. This curve might suggest a single Mendelian factor segregation if 7.5 and 45 percent are accepted as minima, thus dividing the population into 57 resistant, 116 segregating, and 48 susceptible rows. There was an average of 24.0 percent of bunt in segregating rows, which is in fair agreement with the 20.4 percent obtained for F_2. The curve depicted in figure 1 is not greatly different from some published by Briggs (*1*) for plants in which the segregation was that of a dominant resistant gene. The main difference is in the lack of a definite mode for the susceptible group in the cross under consideration here. The spreading effect in the susceptible group may be accounted for by a weak factor, as will be seen presently. There were no segre-

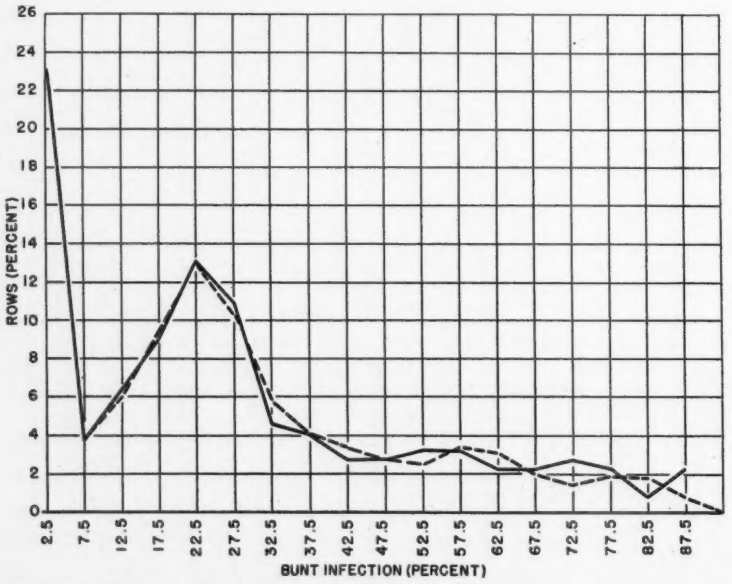

FIGURE 1.—Observed distribution of F_3 rows of Turkey 10016 × Baart for bunt infection (solid line) compared with the theoretical distribution (broken line).

gating or susceptible F_3 rows in the crosses of Turkey 10016 × Turkey 3055, which is the tester for the Turkey factor *T*, and with Rio, which is the tester for the Rio factor *R*. These data indicate that these two genes are present in Turkey 10016. The Rio factor was first reported by Stanford (*8*) in 1941. He showed that the Rio and Turkey genes were closely linked, with an estimated cross-over value of 2.4 percent. The data from Turkey 10016 × Rio were not available until 1943. Prior to that time a genetic analysis based on the Turkey factor and a weak factor pretty well satisfied the available data. Two closely linked genes will give a result similar to a single gene. Therefore it would have been impossible to detect the presence of two genes without the use of test crosses.

As pointed out earlier, a weak gene was postulated to account for the spread among susceptible rows. The addition of a weak factor is needed also to account for the 20.4 percent of bunt in F_2. The percent of bunt to be expected in F_2 rows from the *T* and *R* genes entering the cross in the coupling phase is not known exactly, but it would be considerably above 20 percent. It is not known how much protection heterozygous *T* and *R* (*TtRr*) gives plants, but it is known that about half the plants heterozygous for *T* or *R* become infected. These, together with any infected plants from the *TtRr* group, plus the 22.7 percent of susceptible plants expected, would probably amount to as much as 35 percent of bunted plants. As will be seen later, the weak factor postulated here is found also in Turkey 10015. Therefore there seems little doubt about its presence. For convenience, this gene will be designated as *X*.

The information available on the *X* factor indicates that it allows about 25 percent of bunted plants when homozygous and about 75 percent when heterozygous. The *T* and *R* genes give almost complete protection when homozygous but permit about half the heterozygous plants to become infected. The Rio gene is a little weaker in this respect than the Turkey. As pointed out above, the interaction of genes cannot be calculated accurately as would be the case if only susceptible plants become infected. The values used are consistent with what might reasonably be expected. The final decision as to the exact value used was dictated by the requirements of the distribution observed in figure 1. With the exception of the triple heterozygote, the various genotypes permitting bunt were assigned mean values which were multiples of 2.5 percent. Further refinement did not seem to be justified since it would furnish little additional useful information. In the case of the triple heterozygote, 24 percent was used for the mean because it resulted in a considerably better fit than the 20.4 percent which was observed in F_2.

The proportion of F_2 genotypes, the number of F_3 rows expected from each out of a total of 221 rows, and the percent of bunt expected in F_3 rows are given in table 4. Stanford's cross-over value of 2.4 percent was used for the *T*–*R* relationship. *X* is independent.

No attempt was made to assign values to the F_3 rows marked resistant, although it is recognized that these would differ slightly in resistance. Frequency distributions were calculated for the other genotypes by using the means indicated and standard errors derived from the formula $S=\sqrt{\frac{pq}{n}}$. While this probably underestimates the errors since no account is taken of environmental effects, it does give a distribution which conforms very well to that observed. The separate distributions for the genotypes concerned are shown in table 5.

The combined values of the separate distributions give the number of rows expected for the various classes. The 63.31 resistant rows expected were arbitrarily assigned to the first three classes, using the available rows in the first two classes and placing the remaining in the third class. This resulted in complete agreement between expected and observed rows in the first two classes. However, the agreement between observed and expected beyond this class is very good, as will be seen in figure 1. The χ^2 for classes beyond those to which rows were assigned arbitrarily is 3.5009, which gives a very high probability.

TABLE 4.—*Proportion of F_2 genotypes expected, number of F_3 rows expected out of a total of 221, and percent of bunt expected in F_3 rows of Turkey 10016×Baart*

Proportion of F_2 genotype expected	Number of F_3 rows expected	Mean percent of bunt expected in F_3 rows	Proportion of F_2 genotype expected	Number of F_3 rows expected	Mean percent of bunt expected in F_3 rows
0.0566 $\frac{TR\ X}{TR\ X}$	12.52	(1)	0.00015 $\frac{Tr\ X}{Tr\ X}$	0.03	(1)
.1133 $\frac{TR\ X}{TR\ x}$	25.04	(1)	.0003 $\frac{Tr\ X}{Tr\ x}$	.07	(1)
.0567 $\frac{TR\ x}{TR\ x}$	12.52	(1)	.00015 $\frac{Tr\ x}{Tr\ x}$	.03	(1)
.0057 $\frac{TR\ X}{tr\ X}$	1.26	(1)	.0057 $\frac{Tr\ X}{tr\ X}$	1.26	(1)
.0114 $\frac{TR\ X}{Tr\ x}$	2.52	(1)	.0114 $\frac{Tr\ X}{tr\ x}$	2.52	25
.0057 $\frac{TR\ x}{Tr\ x}$	1.26	(1)	.0057 $\frac{Tr\ x}{tr\ x}$	1.26	40
.0057 $\frac{TR\ X}{tR\ X}$	1.26	(1)	.00015 $\frac{tR\ X}{tR\ X}$	.03	(1)
.0114 $\frac{TR\ X}{tR\ x}$	2.52	(1)	.0003 $\frac{tR\ X}{tR\ x}$	.07	(1)
.0057 $\frac{TR\ x}{tR\ x}$	1.26	(1)	.00015 $\frac{tR\ x}{tR\ x}$	.03	(1)
.1133 $\frac{TR\ X}{tr\ X}$	25.04	17.5	.0057 $\frac{tR\ X}{tr\ X}$	1.26	(1)
.2266 $\frac{TR\ X}{tr\ x}$	50.10	24	.0114 $\frac{tR\ X}{tr\ x}$	2.52	25
.1133 $\frac{TR\ x}{tr\ x}$	25.04	40	.0057 $\frac{tR\ x}{tr\ x}$	1.26	50
.0003 $\frac{Tr\ X}{tR\ X}$	.07	(1)	.0567 $\frac{tr\ X}{tr\ X}$	12.52	25
.0006 $\frac{Tr\ X}{tR\ x}$	.13	(1)	.1133 $\frac{tr\ X}{tr\ x}$	25.04	60
.0003 $\frac{Tr\ x}{tR\ x}$	.07	(1)	.0567 $\frac{tr\ x}{tr\ x}$	12.52	80

[1] Resistant.

Segregation occurred in the crosses of Turkey 10016 with Selection 1403, which carries the Hussar factor *H*, and with Martin, which carries the *M* factor for resistance to bunt. While no extensive analysis has been made of the segregation in these crosses, the number of susceptible and segregating rows are in general conformity with the hypotheses advanced above. The lack of susceptible rows in the crosses with Martin is the result of linkage between the Martin, Turkey, and Rio factors.

The available data clearly show that Turkey 10016 carries the Turkey and the Rio factors for resistance to bunt. An additional weak factor which has been designated *X* is necessary to explain adequately the segregation observed. The data indicate that this factor allows about 25 percent of diseased plants when in the homozygous condition. While such a weak factor has not been previously reported, varieties of wheat with this type of resistance are known to occur. Mackie and Briggs in 1920 (unpublished data) found 6 out of 956 varieties and strains of wheat which showed a bunt infection between 20 and 25 percent. This same weak factor must be considered in explaining the segregation observed in the cross between Turkey 10015 and Baart.

TABLE 5.—*Theoretical distributions of F_3 rows of Turkey 10016 x Baart for the several genotypes indicated*

[Numbers of rows and means used for genotypes are those shown in table 4]

Class centers	*TR* X / *tr* X	*TR* X / *tr x*	*TR x* / *tr x*	*Tr* X / *tr x*	*Tr x* / *tr x*	*tR* X / *tr x*	*tR x* / *tr x*	*tr* X / *tr* X	*tr* X / *tr x*	*tr x* / *tr x*	Resistant rows	Expected rows	Observed rows	x^2/m [1]
											Number	*Number*	*Number*	
2.5	0.19	------	------	------	------	------	------	------	------	------	52.81	53.00	53	------
7.5	1.62	------	------	------	------	------	------	------	------	------	6.38	8.00	8	------
12.5	6.04	2.84	------	0.11	------	0.11	------	0.52	------	------	4.12	13.74	14	------
17.5	9.34	9.23	------	.38	------	.38	------	1.90	------	------	------	21.23	20	0.0713
22.5	6.04	16.44	0.27	.77	------	.77	------	3.85	------	------	------	28.14	29	.0263
27.5	1.62	14.25	1.30	.77	0.06	.77	------	3.85	------	------	------	22.62	24	.0842
32.5	.19	5.97	3.98	.38	.22	.38	0.02	1.90	------	------	------	13.04	10	.7087
37.5	------	1.33	6.97	.11	.36	.11	.07	.52	------	------	------	9.47	9	.0233
42.5	------	------	6.97	------	.36	------	.20	------	------	------	------	7.53	6	.3109
47.5	------	------	3.98	------	.22	------	.34	1.57	------	------	------	6.11	6	.0020
52.5	------	------	1.30	------	.06	------	.34	3.98	------	------	------	5.68	7	.3068
57.5	------	------	.27	------	------	------	.20	6.97	------	------	------	7.44	7	.0260
62.5	------	------	------	------	------	------	.07	6.97	------	------	------	7.04	5	------
67.5	------	------	------	------	------	------	.02	3.98	0.38	------	------	4.38	5	.1766
72.5	------	------	------	------	------	------	------	1.57	1.80	------	------	3.37	6	------
77.5	------	------	------	------	------	------	------	------	4.09	------	------	4.09	5	1.6798
82.5	------	------	------	------	------	------	------	------	4.09	------	------	4.09	2	------
87.5	------	------	------	------	------	------	------	------	1.80	------	------	1.80	5	.0850
92.5	------	------	------	------	------	------	------	------	.38	------	------	.38	------	------
Total	25.04	50.06	25.04	2.52	1.28	2.52	1.26	12.54	25.04	12.54	63.31	221.15	221	3.5009

[1] Square of difference between number observed and number expected, divided by number expected.

INHERITANCE OF RESISTANCE TO BUNT IN HYBRIDS WITH TURKEY 10015

As will be seen in table 1, Turkey 10015 is highly resistant to bunt, although it usually shows a little more of this disease than Turkey 10016.

The F_3 data from crosses of Turkey 10015 with Baart, with the four test varieties and with Turkey 10016, are given in table 3. The segregation with Baart is shown in figure 2. The small proportion of

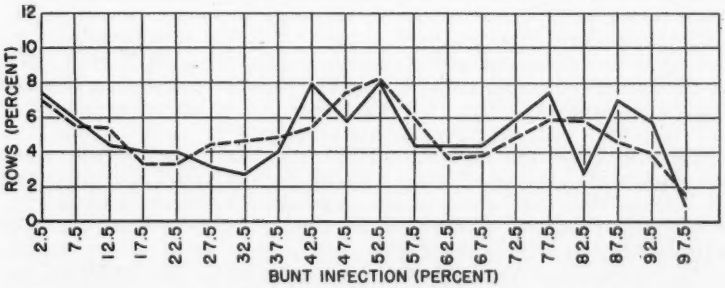

FIGURE 2.—Observed distribution of F_3 rows of Turkey 10015×Baart for bunt infection (solid line) compared with the theoretical distribution (broken line).

highly resistant rows, together with the absence of prominent modes, suggests the lack of a strong factor. Segregation occurred in the crosses with Martin, Turkey 3055, Selection 1403, and Rio, showing definitely that none of the four factors carried by these varieties is present in Turkey 10015. No segregation occurred, however, in the cross with Turkey 10016; these two must, therefore, have the *X* resistant factor in common.

An attempt has been made to satisfy the segregation encountered in the cross with Baart with an analysis which would be consistent with known facts. At best, the interpretation probably only approximates the true condition and therefore the information will have limited usefulness.

Several theories were followed up, assuming the presence of one or two weak factors in addition to the *X* factor which is known to be present. While three weak factors generally gave a slightly better fit than two, the reduction in χ^2 did not seem to be sufficient to justify this theory; therefore the analysis presented is based on two weak factors. The approach was the same as that used for Turkey 10016 ×Baart.

As pointed out above, the standard errors used probably are too small. Again, it should be emphasized that the interaction of factors cannot be predicted accurately from the action of the factors entering into the combination. The F_2 genotypes and the mean percentages of bunt assumed for F_3 rows are given below.

Ratio of F_2 genotype:	*Mean percent of bunt in F_3 rows*	Ratio of F_2 genotype—Con.	*Mean percent of bunt in F_3 rows*
1 *XXYY*	2.5	2 *Xxyy*	72.5
2 *XXYy*	10.0	1 *xxYY*	45.0
2 *XxYY*	32.5	2 *xxYy*	82.5
4 *XxYy*	52.5	1 *xxyy*	92.5
1 *XXyy*	22.5		

The values used for *XX* and *Xx* were 22.5 and 72.5, as compared with 25.0 and 60.0 assigned them on the basis of the data from Turkey 10016×Baart. Since these values are only approximate, the use of slightly different values seems justified. It was assumed that *YY* would permit 45.0 percent of diseased plants and *Yy* 82.5 percent in F_3 rows.

The F_2 data (table 2) indicated that F_3 rows arising from *XxYy* plants should have an average of 42.5 percent of bunt. When such a value was used it was necessary to assign *YY* a very weak value. The interaction of such a weak gene with *XX* would hardly be expected to confer so high a degree of resistance on *XXYY* individuals as that observed. Therefore, a value of 52.5 percent was assigned to the double heterozygote. The values assigned to the other genotypes are consistent with those reasonably expected.

Table 6 shows the distributions for the various genotypes which were calculated for the 226 F_3 rows of Turkey 10015×Baart, using the means indicated above. The agreement between the rows observed and those expected is satisfactory; χ^2 is 18.2597, which gives a probability greater than 0.3.

The segregation observed in the cross between Turkey 10015 and Selection 1403 confirms the above hypothesis, insofar as an analysis has been attempted. On the basis of 3 factors 3.8 susceptible rows would be expected. The exact number present cannot be stated definitely, but it may be assumed that 3 or 4 of the rows present are homozygous for susceptibility. As shown by the distributions in table 6, 60 percent of bunt would roughly divide genotypes *hhXxyy*, *hhxxYy*, and *hhxxyy* from the others. Thus, $\frac{5}{64}$ or 19.2 rows would be expected with percentages of bunt above this point. Fourteen such rows were observed. In the cross of Turkey 10015 with Martin there was 1 row above 60 percent, but in the crosses with Turkey 3055 and

Rio there was none. This deficiency of rows would result from linkage. It is known that the Martin, Turkey, and Rio genes are all linked; therefore all these crosses should show such a deficiency if the *Y* factor is linked with them. With a cross-over of 15 percent, which would put the *Y* gene about an equal distance from the 3 other genes, 4 or 5 rows with bunt above 60 percent would be expected. This is more than was actually observed.

TABLE 6.—*Theoretical distribution of F_3 rows of Turkey 10015 × Baart for the several genotypes indicated*

[Means used for genotypes are those shown in tabulation, p. —]

Classes	*XXYY*	*XXYy*	*XxYY*	*XxYy*	*XXyy*	*Xxyy*	*xxYY*	*xxYy*	*xxyy*	Number of rows expected	Number of rows observed	x^2/m [1]
0–5	12.80	3.10								15.90	17	0.0761
5–10	1.30	11.02			0.20					12.52	13	.0184
10–15		11.02			1.12					12.14	10	.3772
15–20		3.10	0.70		3.34					7.14	9	.4845
20–25			2.67		4.82					7.49	9	.3044
25–30			6.45		3.34		0.19			9.98	7	.8898
30–35			8.64		1.12		.79			10.55	6	1.9623
35–40			6.45	1.84	.20		2.27			10.76	9	.2879
40–45			2.67	5.76			3.82			12.25	18	2.7084
45–50			.70	12.52			3.82			17.04	13	.9578
50–55				16.24			2.27			18.51	18	.0141
55–60				12.52		0.55	.79			13.86	10	1.0750
60–65				5.76		2.50	.19			8.45	10	.2843
65–70				1.84		6.57		0.22		8.63	10	.2175
70–75						9.04		1.85		10.89	13	.4088
75–80						6.57		6.81		13.38	17	.9794
80–85						2.50		10.52	0.25	13.27	6	3.9829
85–90						.55		6.81	3.17	10.53	16	2.8415
90–95								1.85	7.28	9.13	13	.3894
95–100								.22	3.42	3.64	2	
Total	14.10	28.24	28.24	56.48	14.14	28.28	14.14	28.28	14.12	225.78	226	18.2597

[1] Square of difference between number observed and number excepted, divided by number expected.

Obviously, the final test of the above theory will come when selections from Turkey 10015 × Baart are available, each of which is homozygous for the *X* or *Y* factor only.

DISCUSSION AND SUMMARY

A genetic analysis of Turkey 10016 revealed the presence of one weak and two strong factors for resistance to bunt (*Tilletia caries*). The two strong factors were identified as the Turkey factors, previously reported by Briggs (*3*), and the Rio factor, reported by Stanford (*8*). These had been shown by Stanford (*8*) to be linked, with an estimated cross-over of 2.4 percent. Entering the cross in the coupling phase, the segragation was quite similar to that expected from a single strong factor. The complete analysis, therefore, would not have been possible if Turkey 3055 and Rio had not been available to test for the presence of their genes.

A third gene pair designated as *XX* was necessary to explain the type of segregation observed among the more susceptible F_3 rows. This gene was different from any previously reported from this laboratory in that it permitted about 25 percent of bunt when homozygous for resistance. A few varieties are known which permit a like

amount of bunt under similar conditions. The presence of the *X* factor is necessary, furthermore, to explain the lack of segregation in the cross with Turkey 10015.

Turkey 10016 should be a valuable parent for the plant breeder because of the presence of two strong genes for resistance to bunt which are closely linked. Almost 80 percent of the rows homozygous for resistance in F_3 will be homozygous for both pairs of resistant genes.

The genetic analysis of Turkey 10015 left much to be desired. As indicated above, the *X* gene must be present. The presence of an additional weak gene *Y* which permits 45.0 percent of bunt when homozygous for resistance will satisfy the segregation observed in F_3 of Turkey 10015 × Baart. It should be emphasized that other gene combinations and values might satisfy the observed distribution. The one chosen is based on the minimum number of genes. Furthermore, the values assigned to the various genotypes are in accordance with reasonable expectations based on each of the two gene pairs acting alone.

There are some indication that the *Y* gene is linked with the Martin, Turkey, and Rio genes which are known to be linked with each other (*4*, *8*). While it does not seem desirable to stress the probable linkage of the *Y* factor until conclusive evidence is available, it is of interest that three of the four strong genes and probably one of the two weak genes for bunt resistance thus far discovered are carried by a single chromosome pair. Common wheat is a hexaploid species and one in which duplicate and triplicate factors have been reported on several occasions. Since almost no linkage has been reported, this evidence has been used to support the allopolyploid origin of wheat, assuming that similar genes affecting the same character have been contributed by different parent species. No question is raised here regarding the origin of wheat. Multiple factors are known to exist in diploid species. Seven genes for resistance to mildew in barley, which is a diploid species, have been reported from this laboratory (*9*). It would appear that most of the genes for resistance to bunt thus far discovered have been derived from one of the parent species. There is a possibility that these resistant genes have piled up on this chromosome pair as a result of the occasional crossing over between nonhomologus chromosomes or between similar chromosomes of different genomes which is believed to occur in wheat. It does not seem likely that genes for resistance arose by duplication of the same gene since they differ in their reaction to some races of bunt.

The fact that two weak genes acting together confer such a high degree of resistance as that observed in Turkey 10015 is of importance to the plant breeder. Although such genes probably would not be used where strong ones are available, combinations of weak genes might be very useful in breeding for disease resistance in cases where no strong genes are available.

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THE ACTION OF A REPELLENT SPRAY AGAINST THE MEXICAN FRUITFLY[1]

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INTRODUCTION

When studies on repellents for the Mexican fruitfly (*Anastrepha ludens* (Loew)) were begun in Morelos, Mexico, in 1939, it was assumed that an effective repellent would reduce the fruitfly population, and that the reduction could be measured by comparing the numbers of fruitflies caught in traps. During the course of experiments in an orange grove in 1940, however, it was noted that the traps in sprayed trees sometimes yielded more flies than traps in comparable unsprayed trees, although counts on the infested oranges indicated that the sprays may have provided some protection.

This apparent contradiction led to the hypothesis that, although for a short time after the application a reduction in population is accompanied by a reduced catch, there is later an increased catch, owing possibly to the unusual activity of the flies in flitting from one repellent surface to another as the odor of the repellent becomes less pronounced. In other words, a negative phase in the trap catches is followed by a positive phase, each of which may misrepresent the true fruitfly population. The testing of this hypothesis was made the objective of studies in 1941.

METHODS AND MATERIALS

In the experiments in 1940 counts were made every 3 or 4 days, which was long enough after spraying to pass the negative phase completely. Therefore, in testing the hypothesis, counts might be needed two or three times daily, as well as a sufficient number of flies per sample to give a reliable index of the population, and adequate replication for testing the significance of differences. Since the fruitfly population in an orange grove was generally too small to give adequate catches in less than 2 days, mango trees, in which flies are more abundant, were used in these tests. The tests were made in Cuernavaca, in the State of Morelos.

Two trees 14 feet apart were selected; one was sprayed about once a week with the repellent, the other was left unsprayed as a control. Five traps were placed in representative positions in each tree. They were removed during each spray application and replaced when the leaves were dry. Since it was necessary to use knapsack spray equipment and to climb the tree, coverage at the top, which was 30 feet high, was not so good as might have been desired.

The spray mixture was prepared from commercial materials by mixing 135 ml. of a medium-weight mineral oil, 13.5 ml. of oleic acid, and 27 ml. each of amyl acetate, cyclohexylamine, dicyclohexylamine,

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and 99-percent *l*-nicotine. The last four compounds had been found to be repellent to *Anastrepha ludens* in previous experiments. The mineral oil was included as a fixative, and the oleic acid to form a soap emulsifier with the organic bases. The nicotine was isolated from a commercial nicotine sulfate solution (50 percent nicotine) and used without distillation. This mixture was poured into 9 liters of tap water. An emulsion was formed readily, and the entire amount was sprayed on the test tree.

The glass traps contained 200 ml. of a lure consisting of an 8-percent sugar solution fermented by 0.3 gm. of dried beer yeast. The traps were set in the trees on March 25, and the first spray was applied on March 27. Subsequent sprays were applied about once a week until June 30, when the fruit was picked.

TRAP DATA

Counts of *Anastrepha ludens* were recorded usually one-half hour before each spraying and at various intervals after spraying.

To measure the effect of the repellent spray, the total count in five traps from the test tree was compared with a similar total from the control tree. The ratio was used, but to give a reduction in catch the same range as the increase in catch, the ratio was converted to its logarithm. The negative logarithms represented a reduction and the positive logarithms an increase in catch. The trap data, together with the ratios and their logarithms, are given in table 1.

TABLE 1.—*Comparison of trap catches of Anastrepha ludens in a sprayed and an unsprayed mango tree, 1941*

Spray application	Date	Time after spraying[1]	Fruitflies caught in 5 traps		Ratio	Log *R*
			Sprayed tree	Control tree		
	Mar. 27:	*Hours*	*Number*	*Number*		
	7:30 a. m.	−½	65	85	0.76	−0.1
1	1 p. m.	5	10	20	.50	−.30
	6 p. m.	10	28	21	1.33	.12
	Mar. 28:					
	1 p. m.	29	15	18	.83	−.08
	Mar. 31:					
	7:30 a. m.	−½	87	117	.74	−.13
2	12 m.	4	17	22	.77	−.11
	6 p. m.	10	33	16	2.06	.31
	Apr. 1:					
	1 p. m.	29	31	13	2.38	.38
	Apr. 3:					
	7:30 a. m.	−½	102	76	1.34	.13
	12 m.	4	9	16	.56	−.25
3	6 p. m.	10	31	33	.94	−.03
	Apr. 4:					
	1 p. m.	29	20	11	1.82	.26
	Apr. 5	50	51	34	1.50	.18
	Apr. 7		184	133	1.38	.14
	Apr. 11		225	283	.80	−.10
	Apr. 15:					
	7:30 a. m.	−½	372	347	1.07	.03
4	11 a. m.	3	12	50	.24	−.62
	6 p. m.	10	173	196	.88	−.05
	Apr. 16:					
	11 a. m.	27	99	79	1.25	.10
	Apr. 18		422	518	.81	−.09
	Apr. 21:					
	7:30 a. m.	−½	485	570	.85	−.07
5	11 a. m.	3	55	47	1.17	.07
	6 p. m.	10	221	207	1.07	.03
	Apr. 22:					
	12 m.	28	192	137	1.40	.15
	Apr. 25		901	962	.94	−.03

See footnote at end of table.

TABLE 1.—*Comparison of trap catches of Anastrepha ludens in a sprayed and an unsprayed mango tree, 1941*—Continued

Spray application	Date	Time after spraying [1]	Fruitflies caught in 5 traps		Ratio	Log R
			Sprayed tree	Control tree		
	Apr. 29:	*Hours*	*Number*	*Number*		
	7:30 a. m.	−½	992	942	1.05	.02
6	11 a. m.	3	63	79	.80	−.10
	6 p. m.	10	108	153	.71	−.15
	Apr. 30:					
	11 a. m.	27	147	152	.97	−.01
	May 2		588	587	1.00	.00
	May 6:					
	7:30 a. m.	−½	718	709	1.01	.01
7	11 a. m.	3	16	29	.55	−.26
	6 p. m.	10	106	86	1.23	.09
	May 7:					
	11 a. m.	27	55	57	.96	−.02
	May 9		608	679	.90	−.05
	May 12:					
	7:30 a. m.	−½	379	324	1.17	.07
	12 m.	4	18	25	.72	−.14
8	7 p. m.	11	79	26	3.04	.48
	May 13:					
	11 a. m.	27	32	22	1.45	.16
	5:30 p. m.	33½	74	84	.88	−.05
	May 15		165	205	.80	−.09
	May 19:					
	8 a. m.	−1	226	325	.70	−.16
9	12 m.	3	3	2	1.50	.18
	6 p. m.	9	18	23	.78	−.11
	May 20:					
	12 m.	27	36	54	.67	−.18
	May 23		385	372	1.03	.01

[1] A minus sign indicates the time before spraying. Each spray was applied at 8 a. m. except No. 9, which was applied at 9 a. m. Where no figure is given, the exact time of examination was not recorded.

EFFECT OF REPELLENT SPRAY

The effect of the repellent spray on the trap catch is illustrated by the histogram in figure 1. The mean value (−0.024) of the log R values for the catch before the application of spray was used as the base of the histogram rather than zero. The mean log R value for counts made 3 to 5 hours after spraying was −0.170, for counts after 9 to 11 hours 0.076, after 27 to 29 hours 0.084, and after 3 to 4 days −0.012. The shaded rectangles therefore indicate approximately the negative, positive, and equilibrium phases of the catch.

The log R values were examined statistically by the method of the analysis of variance. The significance of the variance between results for certain time intervals was first determined. These values for 3 to 5 hours after spraying were taken as a measure of the negative phase of the catch. The values obtained from the count at 9 to 11 hours were omitted, except as explained later, because they usually fell between the depth of the negative phase and the peak of the positive phase, and in replicate trials the catch at this time would be positive or negative depending on whether the field conditions increased or decreased the evaporation of the repellent. Inclusion of this count would be expected to give an unfavorable bias to the experimental error, since no effort was made to control the evaporation of the repellent, but only the relative catch of *Anastrepha ludens*.

The appropriate measure of the positive phase of the catch under field conditions could not be expected at the same time after spraying

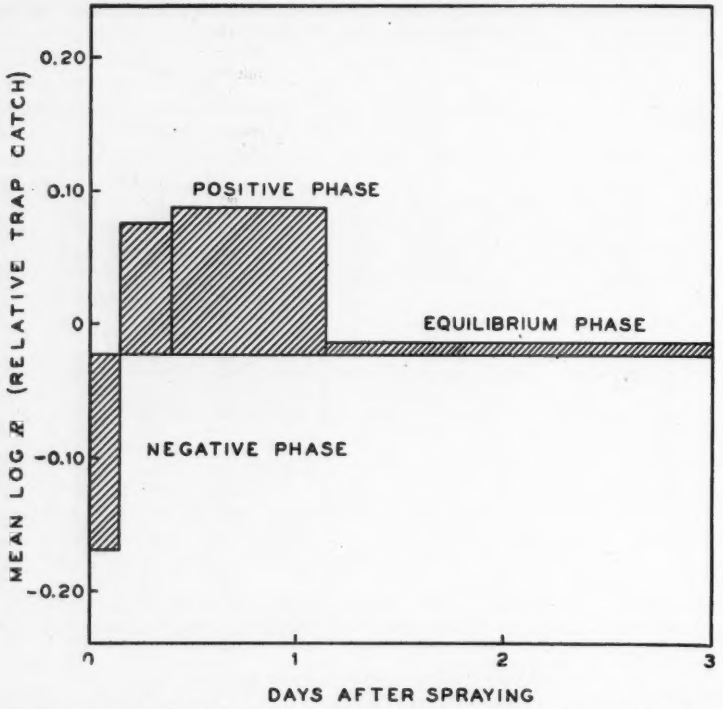

FIGURE 1.—The effect of repellent spray on trap catch of *Anastrepha ludens*.

in all applications. For example, following applications at relatively high field temperatures, wind velocities, and evaporation rates, the trap catch would pass through the negative phase and into the positive faster than after other applications. A continuation of those conditions would lead to the evaporation of the small amount of repellent substance required to maintain the positive phase and hasten the return to equilibrium. Therefore, an attempt to take the measure of the positive phase at any fixed time after spraying, such as 27 to 29 hours, would result in its underestimation. The desired arrangement would be to follow the curve continuously along with appropriate weather records, but counts must be large enough to give a reliable ratio and often several hours are required. In the analysis of the data the peak ratio of the positive phase has been used, provided a negative phase immediately after spraying was followed by a positive phase.

The analysis of variance was used to test the significance of the negative and positive phases, but not their significance at any given time, although it was relatively easy to fix the measure of the negative phase at 3 to 5 hours. The positive phase was measured after six applications at 27 to 29 hours and after three applications at 9 to 11 hours. Since the first three applications were made only 4 and 3 days apart, the equilibrium value for each of the first two applications is the same as the before-spraying value for the succeeding application. The differences between the before-spraying and equilibrium values

were generally so small as to make very little change in the variance. Toward the end of the experiment there was noticeable protection of the sprayed fruit. Therefore, spraying was continued to save the fruit rather than to extend the trap data, and counts were taken after 3 or 4 hours as a routine check on the repellent action. In three out of four applications the reduction in catch was 40 percent or more. The data as analyzed are given in table 2.

TABLE 2.—*Comparative trap catch of Anastrepha ludens, in a sprayed and an unsprayed tree, expressed as log ratios, before spraying and in different phases after spraying*

Spray application	Trap catch of *A. ludens*—				
	Before spraying	After spraying			Total
		Negative phase	Positive phase	Equilibrium phase	
1	−0.12	−0.30	[1] 0.12	−0.13	−0.43
2	−.13	−.11	.38	.13	.27
3	.13	−.25	.26	.14	.28
4	.03	−.62	.10	−.09	−.58
5	−.07	.07	.15	−.03	.12
6	.02	−.10	−.01	.00	−.09
7	.01	−.26	[1] .09	−.05	−.21
8	.07	−.14	[1] .48	−.09	.32
9	−.16	.18	−.18	.01	−.15
Total	−0.22	−1.53	1.39	−0.11	−0.47
Mean [2]	−.024	−.170	.154	−.012	

ANALYSIS OF VARIANCE

Source of variation	Degrees of freedom	Sum of squares	Variance
Application	8	0.2099	0.02624
Phase	3	.4754	[3] .15847
Error	24	.6801	.02834
Total	35	1.3654	

[1] 9- 10-hour values.
[2] Minimum significant difference between means, 0.164.
[3] Highly significant.

The analysis of variance measures the degree of significance of the differences indicated graphically in figure 1. The repellent spray produced a highly significant shift in the comparative trap catches of *Anastrepha ludens* in the two trees. The mean for the positive phase was significantly different from that before spraying and that for the equilibrium phase. The experimental data therefore strongly indicate the existence of the negative phase followed by a positive phase in the action of a repellent on the trap catch of *A. ludens* in a mango tree.

EFFECT OF TIME OF DAY

As a check on the conclusions drawn from the foregoing analysis, the ratio of the trap data in the two trees was studied without the presence of repellent spray. McPhail [2] has shown how the trap catch varies during the day, with relatively small catches early in the morning and late in the afternoon. Presumably these differences would occur in both test and control trees, and the ratio would remain constant during the entire day.

[2] MCPHAIL, M. RELATION OF TIME OF DAY, TEMPERATURE AND EVAPORATION TO ATTRACTIVENESS OF FERMENTING SUGAR SOLUTION TO MEXICAN FRUITFLY. Jour. Econ. Ent. 30: 793–799, illus. 1937.

The uniformity trials were run during the spray program when the ratio had returned to equilibrium after a spray application. Counts were taken late in the afternoon, early in the morning, and in the late forenoon. The data are presented in table 3.

TABLE 3.—*Comparison of the trap catch of Anastrepha ludens in the 2 mango trees without the presence of repellent spray, 1941*

Uniformity trial	Date	Fruitflies caught in 5 traps		Ratio	Log R
		Test tree	Control tree		
		Number	*Number*		
1	Apr. 22: 6:30 p. m.	235	220	1.07	0.03
	Apr. 23: 7:30 a. m.	6	20	.30	−.52
	11:30 a. m.	146	112	1.30	.12
	6 p. m.	158	163	.97	−.01
2	Apr. 24: 7:30 a. m.	21	55	.38	−.42
	11:30 a. m.	147	159	.92	−.03
	6 p. m.	111	175	.63	−.20
3	Apr. 25: 7:30 a. m.	1	6	.17	−.78
	11:30 a. m.	76	52	1.46	.16
	Apr. 30: 6 p. m.	234	241	.97	−.01
4	May 1: 7:30 a. m.	23	33	.70	−.16
	11:30 a. m.	96	111	.86	−.06

From an inspection of the data it seems likely that the first flies caught in the morning are in the control tree, and that any experiment based on catches between 6 p. m. and 7:30 the following morning will be biased in favor of a larger catch in the control tree.

In the repellent-spray experiment the catches from 6 p. m. to 7:30 a. m. were combined for analysis with either the forenoon or the afternoon catches. The appropriate uniformity trials for the experiment would therefore consider the night counts combined with one of the other counts. Since combining with afternoon counts introduces the greater variation, the data were analyzed in that manner. The combined data in terms of log R and a summary of the analysis are presented in table 4.

TABLE 4.—*Comparison of afternoon-night and forenoon trap catches in test and control mango trees without the presence of the repellent spray, expressed as log ratios*

Uniformity trial	Afternoon-night	Forenoon	Total
1	0.00	0.12	0.12
2	−.09	−.03	−.12
3	−.21	.16	−.05
4	−.03	−.06	−.09
Total	−.33	.19	−.14

ANALYSIS OF VARIANCE

Source of variation	Degrees of freedom	Sum of squares	Variance
Trial	3	0.0172	0.0057
Time of day	1	.0338	.0338
Error	3	.0441	.0147
Total	7	.0951	

The variation due to time of day is shown to be considerably less than significant. The variation that does exist was acting to reduce the measurable effect of the repellent rather than to increase it, since the value of log R tended to be more positive in the forenoon than in the afternoon, whereas the application of the repellent produced a value that was negative in the forenoon and became more positive in the afternoon. While more uniformity trials would have been desirable, there is no evidence that the observations attributed to the action of the repellent could have been due to natural variation alone.

PROTECTION OF FRUIT

After the first week in May some evidence developed that the repellent spray might be providing some protection against infestation. Therefore, the weekly spray program was continued to the end of June to compare the infestations of mangoes from the two trees. During June the fallen fruit was counted and examined. On June 30 a large portion of the fruit was picked from the treated tree, and a sample from the control tree was held for comparison. A summary of the fruit records is given in table 5.

TABLE 5.—*Comparison of infestation in fruits from sprayed and control mango trees, 1941*

FALLEN FRUITS

Date	From sprayed tree		Doubtful, between trees		From control tree	
	Total	Visibly infested	Total	Visibly infested	Total	Visibly infested
	Number	*Number*	*Number*	*Number*	*Number*	*Number*
May 30-June 3	8	5	8	3	19	14
June 9	10	7	9	7	30	22
June 17	39	30	22	15	65	37
June 24	37	29	12	12	45	39
June 30	55	46	21	18	120	78
Total	149	117	72	55	279	190
Percent visibly infested		78.5		76.4		68.1

PICKED FRUITS

Side of tree	Sprayed tree			Control tree		
	Total	Infested		Total	Infested	
	Number	*Number*	*Percent*	*Number*	*Number*	*Percent*
East:						
7–10 feet	176	41	23.3	110	60	54.5
10–14 feet	46	13	28.3			
South	99	57	57.6			

The experiment was not designed in such a way that a conclusive result could be expected. The spray coverage was only fair. The differences observed generally indicate less infestation in the sprayed tree.

The fallen fruit was examined every 3 or 4 days, but the data were combined in the table. There is little difference in the percentage of visible infestation in fallen fruit between the sprayed tree and the control tree, because the fruit that falls in Cuernavaca is nearly all

green and damaged by *Anastrepha ludens*. Since previous experience has shown that more than 90 percent of the fruit falling in June and July is infested, if the fallen fruit had been held for later observation many of the mangoes that appeared sound would have been found to be infested. Nearly twice as many fruits fell from the control tree as from the sprayed tree, and the difference was nearly as great for visibly infested fruits.

The picked fruit was held for 8 days at 23° to 25° C. before it was examined, which was 14 days after the last spray had been applied. The east side of the tree appeared to be less heavily infested than the south side. The appropriate comparison indicates that the infestation of the fruit on the control tree was about twice that of the sprayed tree.

Another indication that the repellent spray provided some protection was the fact that the top of the test tree, where coverage was poor, supplied a large part of the fallen fruit. On June 30, when the mangoes were picked, most of the fruit in the top of the tree had fallen but most of the fruit on the branches 10 to 14 feet high remained. The groups of treated fruit were evenly colored, whereas groups of untreated mangoes generally showed spots of premature color due to infestation.

In March the sprayed tree produced a small early crop of mangoes which was almost completely infested.

During the spray program an occasional ripe mango was available for tasting. Mangoes that had received as many as 10 sprays showed no off flavor, but those tasted at the end of the spray program were of poor flavor. No injury to foliage was observed, but oil spots developed on the fruit.

SUMMARY

In previous tests with repellent sprays against the Mexican fruitfly (*Anastrepha ludens* (Loew)) in Mexico, it was found that traps in sprayed trees sometimes yielded more flies than comparable traps in unsprayed trees, although the repellent seemed to provide protection to the fruit. An experiment was therefore undertaken to test this apparent contradiction. Traps containing a fruitfly lure were set out in two mango trees, and one tree was sprayed about once a week from March 27 to June 30, while the other tree was left unsprayed. The flies caught in the traps were counted before each spraying and at various intervals (usually 3 to 5, 9 to 11, and 27 to 29 hours) after spraying, and the ratios of the counts in the two trees were analyzed statistically.

The repellent action was found to pass through two phases in its effect on the trap catch—a negative phase following the application of the repellent, during which the catch in the sprayed tree was lower than in the unsprayed tree, and a positive phase in which the catch in the sprayed tree was above normal.

Uniformity trials run when the catches had returned to equilibrium after an application indicated that the differences were due to the action of the repellent and not to natural variation.

A comparison of infestation in fruits from the sprayed and the unsprayed tree showed that the spray probably provided some protection to the fruit.

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